FIRE HISTORY FROM FOSSIL CHARCOAL IN LAKE AND SWAMP SEDIMENTS

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Except where otherwise acknowledged, this thesis represents my own work. Pollen and charcoal analyses of the top 4.5m of the 12m of sediment in Lashmar's Lagoon, described in Chapter 7.1, were included in my thesis submitted to Monash University in 1976 for a B.Sc.(Hons) degree.

Robin Lorraine Clark

Frontispiece. An experimental fire on Black Mountain, A.C.T. (Chapter 5.2). Smooth-barked trees are *Eucalyptus rossii*.

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ABSTRACT

Several approaches are taken to the problems of reconstructing fire history from charcoal preserved in lake and swamp sediments and analysed along with pollen. The differing effects on charcoal of sample preparation techniques are investigated and the usual pollen preparation procedure is recommended for concentrating charcoal. A simple and rapid method of quantifying charcoal in pollen preparations by point count estimation of projected area is introduced and it is shown how the method can also be applied to thin sections of sediments to estimate the annual input volume of charcoal.

The production and transport of charcoal are discussed and it is argued that models of charcoal transport are not useful for deducing the locations of fires from charcoal assemblages in sediments. Experiments are described in which the amount of charcoal produced by and transported from present-day fires is estimated. It is found that most charcoal remains in a burned area and more is removed in suspension in water than is carried away in smoke. Thus, most charcoal in a sedimentary basin comes from its water catchment and areas close to, but outside, its catchment. The charcoal catchment is unlikely to be the same as the pollen catchment. The sedimentary charcoal record is of fire-rainfall events, not of fires alone.

Deposition of charcoal in sediments is discussed and it is shown that either more or less frequent fires may increase the amount of charcoal deposited over a given time, depending mainly on the rate of fuel accumulation. A model is devised to show how the relationship between true and apparent fire histories may be affected by the sediment sampling scheme. Examples are provided of the use of pollen

and charcoal to reconstruct vegetation and fire histories of three sites in South Australia. At one site, the amount of charcoal in sediments appears better related to the history of deposition and preservation than to that of fires.

Comparison of the amount of charcoal in sediments from sites in Australia and New Guinea demonstrates that similar or different fire regimes may be identified at sites with comparable vegetation and catchments, and that the impact on vegetation of people using fire might be clearly distinguishable only in areas where natural fires were previously absent or rare.

Expressing charcoal quantities as amount per unit dry weight of inorganic sediment is shown to be more informative than as amount per unit volume of wet sediment. Size distributions of charcoal particles are considered, but do not appear to be useful for interpretation.

The difficulties of discerning past effects of Aboriginal burning on the vegetation of Australia are discussed and assumptions about Aboriginal use of fire and its effects are questioned. It is concluded that Aborigines neither created nor maintained large areas of grassland and that climate has been more important than fire in determining vegetation distribution.

The sedimentary charcoal record of fire history is an imperfect one, but its interpretation, based on an awareness of the complexities of the processes involved, is the best means available for studying the long-term effects of fire regimes on vegetation.

NOTES

Authorities for plant names used in the text may be found in Black (1943-1957), Eichler (1965) and Willis (1970-1972) for South Australian species and in Burbidge and Gray (1976) for species in the Australian Capital Territory and nearby New South Wales.

The terminology of Beadle and Costin (1952) has been used throughout to describe Australian vegetation types. Their system is more appropriate to palynological reconstructions of vegetation than the classification of Specht (1970) because the structure of past vegetation and its floristic composition at the species level can rarely be inferred from the pollen evidence. In the text, a term from Specht's classification is sometimes given as well as one from Beadle and Costin's.

CONTENTS

Chapter 1

INTRODUCTION

Fire is increasingly used to manage vegetation for grazing, forestry and recreation, and to control the spread of wildfires by reducing fuel (Mooney and Conrad, 1977; Gill, Groves and Noble, 1981, Section 5; Conrad and Oechel, 1982, Part 6). Little is known of the long-term effects on vegetation of such imposed fire regimes, defined as combinations of the frequency and intensity of fires, the season of burn and fire type (Gill, 1975, 1981b). Observations over years or decades are insufficient for predicting changes in vegetation composed of species whose life spans might extend to hundreds, or even thousands, of years. The study of fire history can provide the long-term information necessary for intelligent management of present vegetation for the future.

The main sources of evidence for fire history are: (a) the composition and distribution of present vegetation in relation to the adaptations and responses of individuals, populations, species and communities to different fire regimes; (b) vegetation history, reconstructed from pollen preserved in sediments and interpreted in terms of present-day responses to fire; (c) tree-rings and their fire scars; (d) historical and ethnographic records; and (e) charcoal preserved in sediments. It is with the possibilities and limitations of the evidence from charcoal that this thesis is concerned.

Microscopic charcoal fragments (Figure 1.1) have long been a familiar sight to those studying pollen and other microfossils preserved in lake and swamp sediments. Iversen (1941, 1952, 1964,

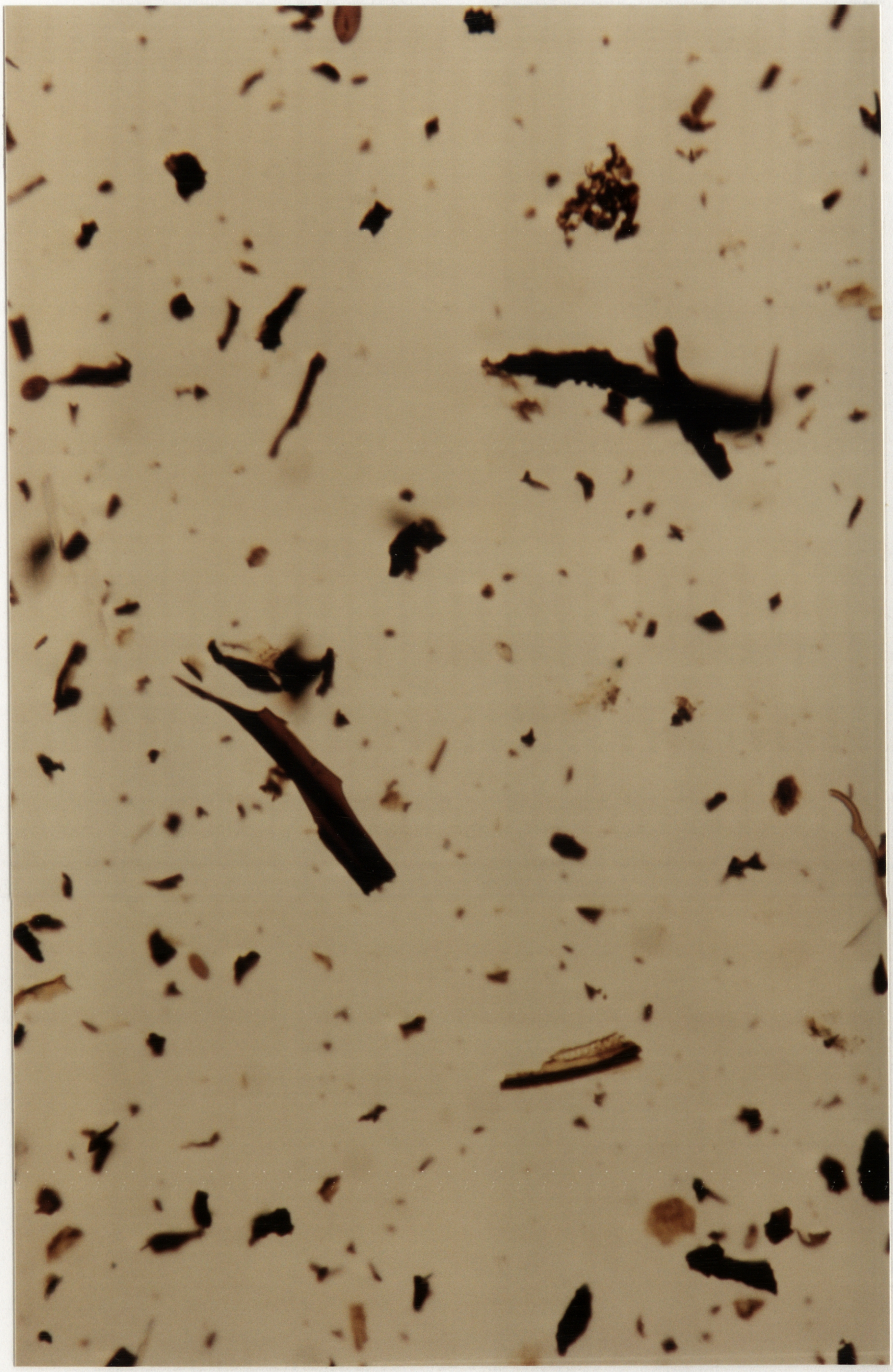


Figure 1.1. Charcoal fragments in a pollen preparation from Lashmar's Lagoon sediments (Chapter 7.1). Magnification is x1000.

1969) first quantified the charcoal in pollen preparations and drew conclusions about the fire history of his sites, relating this to the histories of both vegetation and human settlement. It was not until the 1960's that others followed Iversen's initiative (e.g., Hutchinson and Goulden, 1966; Davis, 1967; Fredskild, 1967; Tsukada and Deevey, 1967). The work of Waddington (1969), who introduced the measurement of particle area in size-classes and of Swain (1973), who showed that charcoal preserved in sediments reasonably reflected fire history reconstructed from other evidence, provided the impetus for many further studies (e.g., Bradbury and Waddington, 1973; Byrne et al., 1977; Cwynar, 1978; M. Tolonen, 1978; Amundson and Wright, 1979). Charcoal analyses, mainly on material from sites in Europe and North America, have been critically reviewed by Patterson (unpublished) and K. Tolonen (in press) and are included in Alexander's (1979) bibliography of studies on fire history.

In Australia, Churchill (1968) noted the presence of charcoal in many samples from Western Australia sites and, later, Macphail (1980), working on Tasmanian sediments, distinguished samples with abundant charcoal from those with little or none. The first quantitative studies in Australia of charcoal in pollen preparations were made on material from New Guinea (Hope and Peterson, 1976; Hope, 1983a and b; Corlett, 1979; Garrett-Jones, 1979). Several quantitative charcoal analyses of sediment samples from Australian sites have been completed (Clark, 1976; Hooley, et al., 1980; Polach and Singh, 1980; Clark and Lampert, 1981; Crowley, 1981; Singh, 1981a; Singh, Kershaw and Clark, 1981; Head, 1983) and many more are in progress (Thom and Wasson, 1982).

The analysis of charcoal to reconstruct fire histories has led to valuable insights into the dynamics of vegetation and of human interaction with the environment. But there are great difficulties in relating the abundance of charcoal in sediments to past fires and in separating the effects of fires on vegetation from those of shifts in climate, changes in soils, actions of people or interactions between plant species or populations which may lead to changes in floristic composition over shorter or longer terms.

The work described in this thesis attempts to define more closely what can or cannot be deduced about fire history from fossil or sub-fossil charcoal preserved in lake and swamp sediments and sampled, processed and analysed along with pollen to reconstruct vegetation history. Chapter 2 discusses the identification of microscopic charcoal fragments in pollen preparations and the effects on charcoal of sample preparation procedures. Methods of estimating the amount of charcoal are considered in Chapter 3 and a technique that is faster and simpler than current methods is introduced. The transport of charcoal from burned vegetation to deposition sites is discussed in theoretical terms in Chapter 4, while Chapter 5 describes collections of charcoal produced by and transported from present-day bushfires. Chapter 6 considers the mechanisms of charcoal deposition and the problems of relating the quantities of charcoal in samples to the true fire history. Reconstructions of fire and vegetation history from three sites are given in Chapter 7 and the results from these analyses are compared with those from present-day fires in Chapter 8, which also suggests more informative methods of presenting results than those commonly used. Chapter 9 considers the application of charcoal analysis to a specific problem: what effect has Aboriginal burning had on the vegetation of Australia? Chapter 10 draws general conclusions and suggests further research.

Some of the work described in Chapters 3, 7 and 9 has been published (Clark, 1981, 1982; Clark and Lampert, 1981; Singh, Kershaw and Clark, 1981), is in press (Clark, 1983), or is at an advanced stage of preparation (Hope, Clark and Hope, in prep.). Rather than including the papers in the thesis, their contents have been integrated in the appropriate chapters. Pollen and charcoal analyses of the top 4.5m of the 12m Lashmar's Lagoon sediment cores were included in a B.Sc.(Hons) thesis submitted to Monash University (Clark, 1976).

In the course of that earlier study (Clark, 1976), several difficulties with interpretation of the charcoal record became apparent. In particular, the assumption that the presence of people leads to more frequent fires which increase the amount of charcoal in sediments was found not to hold for the results from Lashmar's Lagoon. The question of how the charcoal record might change in response to changes in fire regime, particularly in the frequency or intensity of fires, is one of several threads which run through this thesis. Others include: What is the source area of charcoal? How is charcoal transported to sediments? What happens to it after deposition? How does the charcoal in sediments relate to past fires? Do changes in fire regime necessarily alter vegetation? How do study techniques affect interpretation? Can conclusions drawn from studies on one time-scale be applied to very different time-scales? Some of these questions are raised early in the thesis but no answers attempted until later chapters when all relevant data have been presented.

Because so little previous work had been done on the techniques of charcoal analysis and the interpretation of results and because most of the questions raised are interdependent, a multi-faceted approach appeared necessary, with several lines of investigation being followed concurrently. This approach meant that the amount of time devoted to the various parts of the project was not necessarily related to their eventual importance to the whole, and that methodology changed as better techniques were developed (e.g., the direct observation of samples on cellulose nitrate filters described in Chapter 2 and the point count method detailed in Chapter 3). There were severe limitations imposed by the availability of experimental fires and the unpredictability of wildfires. The results might have been improved if time and fires had been more abundant so that a logical sequence of investigations could have been followed. Suggestions for continuing research are made in the concluding chapter.

Some of the work described in this thesis has applications in other fields, but the methodology was chosen to answer one basic question: what can be learned about fire history from charcoal preserved in lake and swamp sediments to enhance reconstructions of vegetation history from the pollen record?

Chapter 2

CHARCOAL AND PREPARATION METHODS

Charcoal is produced by the incomplete combustion of organic materials. Differential shrinking as dehydration progresses leads to fracturing of tissues and the production of charcoal fragments ranging in size from sub-microscopic to several cubic centimetres. As charcoal is brittle, larger fragments may easily be broken into smaller. Charcoal retains the form of the plant material from which it derived and individual fragments may consist of whole organs, such as leaves, parts of tissues, such as wood, whole cells or pieces of cell walls. The microscopic charcoal particles encountered in pollen preparations (Figure 1.1) are usually groups of cells, whole cells or parts of cell walls, although globules of tars may also be found (K. Tolonen, in press; Chapter 5.1).

Charcoal is often described as a form of amorphous carbon (Humphreys and Ironside, 1980) but Shneour (1966) pointed out that all "amorphous" carbons are microcrystalline graphites whose properties reflect defects in the lattice structure of carbon. The carbon, hydrogen and oxygen content of charcoal and the amount of charcoal produced from plant tissues are dependent on the temperature of carbonization. As the temperature increases, the hydrogen and oxygen content and the yield of charcoal decrease (Humphreys and Ironside, 1980). Ash contents of charcoal vary considerably (Humphreys and Ironside, 1980). In any one fire, charcoal will be produced from plant materials of different chemical composition and at a range of temperatures, pressures and oxygen availabilities. The elemental carbon content of naturally-produced charcoal will thus vary greatly.

Charcoal in soils may be very slowly oxidized to carbon dioxide, and Shneour (1966) has demonstrated that this process may be accelerated by the action of microorganisms. Charcoal is removed from burned areas by oxidation or erosion and, depending on the sedimentary environment, deposited charcoal may also be subject to physical, chemical or biological degradation.

Preparation procedures used for concentrating the pollen and charcoal in sediment samples include severe chemical and physical treatments, so it is likely that charcoal is affected by these procedures. This chapter describes investigations of the effects of sample preparation on charcoal and considers the problems of distinguishing microscopic charcoal fragments from other black particles.

Pollen preparation procedures

The procedure used for the preparation of sediment or peat samples for pollen analysis consists of physical and chemical treatments designed to remove inorganic material and all but the most resistant organics, which include pollen. The basic procedure, as described by Gray (1965) and Faegri and Iversen (1975), is used world-wide, variations depending on the nature of the sediment or peat, the question being investigated, the laboratory facilities available or the personal preferences of the preparator. Details are given below of each procedural step used in the preparation of samples for the studies described in this thesis. The steps used in the preparation of each group of samples will be indicated as results are presented. All centrifugations, unless otherwise specified, are at 2500-3000rpm for one minute; all water added to samples has been distilled.

1. Hydrochloric acid (HCl). Removes carbonates, sulphates, etc. Usually only applied if a test for carbonates is positive.

   Add 10% HCl to sample (10% of concentrated, *i.e.*, 35% HCl); place in boiling water bath for 10-30 minutes or until reaction ceases.

   Centrifuge, decant.

   Add water, centrifuge, decant (twice).

2. Hydrofluoric acid (HF). Removes silicates.

   Add 40% HF to sample in polypropylene centrifuge tube; either leave for 24 hours or place in boiling water bath for 1 hour.

   Centrifuge, decant.

   Add water, centrifuge, decant (four times).

   Add 10% HCl; place in boiling water bath for 10-15 minutes.

   Centrifuge, decant.

   Add water, centrifuge, decant (twice or more, until neutral).

3. Potassium hydroxide (KOH). Deflocculates by removal of organic soil colloids. Removes phenolic decomposition products. Sodium hydroxide, up to 5%, may be used instead.

   Add 10% KOH; place in boiling water bath for 2-10 minutes.

   Centrifuge, decant.

   Add water, centrifuge, decant (twice).

4. Sieving. Removes large detritus.

   Sieve through a brass mesh sieve or terylene mesh of size between 150µm and 250µm.

5. Zinc bromide density separation ($ZnBr_2$). Removes mineral grains.

   Add 10% HCl; place in boiling water bath for 5 minutes.

   Centrifuge, decant.

Add $ZnBr_2$ solution, specific gravity ≃ 2.0 (500g $ZnBr_2$ in 198ml water acidified with 10% HCl).

Centrifuge at 1500 rpm for 15 minutes.

Pipette off organic float fraction; collect in new tube.

Acidify with few drops 10% HCl.

Add water; shake vigorously.

Centrifuge at 4500 rpm for 5 minutes, decant.

Add water, centrifuge, decant (twice).

6. Acetolysis. Removes cellulose by acetylation.

Add glacial acetic acid, centrifuge, decant (twice).

Add 9 parts acetic anhydride and 1 part sulphuric acid; place in boiling water bath 7-15 minutes.

Centrifuge, decant.

Add glacial acetic acid, centrifuge, decant (twice).

If not proceeding to sodium chlorate:

Add water, centrifuge, decant (four times).

7. Sodium chlorate ($NaClO_3$). Oxidizes lignin; bleaches organics, including insect cuticle. Sodium chlorite ($NaClO_2$) or potassium chlorate ($KClO_3$) may also be used.

To sample in acetic acid after decanting, add 5-6 drops saturated $NaClO_3$ solution and 1ml concentrated HCl.

If there is an immediate colour change, add water; if not, add water after 10-15 seconds.

Centrifuge, decant.

Add water, centrifuge, decant (four times).

8. Staining

Add 45% ethanol, centrifuge, decant.

Add 2-10 drops 0.04% Safranin O solution in water.

Leave 20 sec (if sodium chlorate has not been used, 30-60 sec in a hot water bath may be necessary).

Add 45% ethanol, centrifuge, decant.

9. Dehydration and mounting

Add 45% ethanol, centrifuge, decant.

Add 80% ethanol, centrifuge, decant.

Add 95% ethanol, centrifuge, decant.

Add 100% ethanol, centrifuge, decant (twice).

Add tertiary butyl alcohol (TBA), centrifuge, decant (three times).

Transfer sample with small quantity of TBA to small storage vial.

Add silicone oil of viscosity 2000 centistokes.

Leave vial open for 24 hours in a dust-free cabinet, or heat at 60°C for a shorter time, to evaporate TBA.

After thorough stirring, pipette sample suspension to microscope slides under coverglasses.

Stronger oxidizing agents may be used to remove some minerals, including pyrites and other sulphides, and organic materials. The two oxidants most commonly used are:

10. Nitric acid (HNO_3)

Add concentrated (70%) HNO_3 to half fill tube; place in boiling water bath for 10 minutes.

Add water, centrifuge, decant.

Add 5% ammonia; place in boiling water bath for 15 minutes.

Centrifuge, decant.

Add water, centrifuge, decant (four times).

11. Schulze solution ($NaClO_3$ + HNO_3).

Prepare solution by mixing 1 part saturated solution of $NaClO_3$ with 2 parts concentrated (70%) HNO_3.

Add solution to samples; place in boiling water bath for 5 minutes.

Add water, centrifuge, decant (four times).

Throughout processing, a vortex stirrer is used when necessary to resuspend samples. In addition, fine material may sometimes be removed by use of an ultrasonic bath for 10-30 seconds, followed by centrifugation at 1000-1500 rpm for 30-60 seconds and decanting. This is usually carried out when the sample is in water prior to zinc bromide density separation or before dehydration.

Will other black particles which might be confused with charcoal be removed by the pollen preparation procedure? The sediments might contain pyrite crystals and other black minerals, dark plant fragments, black insect cuticles and organic materials carbonized by means other than fire. Density separation of organics from inorganics will remove all minerals if inorganic particles are not attached to lighter organics. If this step is not used, some acid-soluble minerals will be removed by hydrochloric and hydrofluoric acids, while concentrated nitric acid can be used to remove pyrites and other sulphides. Many minerals are distinguishable by their crystalline form or by their birefringence in polarized light. Dark plant fragments are removed or bleached by the acetolysis and potassium hydroxide steps, which are almost always included in pollen preparation procedures, and by sodium chlorate or stronger oxidation. Insect cuticles often retain their structure and are immediately recognizable; sodium chlorate with hydrochloric acid will bleach most cuticular fragments.

Organic materials carbonized by means other than fire have the same chemical and physical properties as charcoal, so will react similarly to the preparation procedure. Cope and Chaloner (1980) provide evidence that the middle lamella of plant cell walls is destroyed by carbonization at high temperatures but not by that at low temperatures and suggest that this distinction may be used to identify charcoal. Even if this distinction proved valid, it would be of little use in charcoal analyses as cross-sections of cell walls of charcoal particles are rarely visible in pollen preparations. There is much confusion in the literature about how, other than by fire, plant material may be carbonized. Coal petrologists have speculated on whether fusains originated as charcoal from forest fires or as peats carbonized by either oxidation or reduction (Harris, 1958; Staplin, 1969; Teichmüller, 1975). Friedel, et al. (1970) carbonized plant material by maintaining it at 200°C in a sealed, evacuated glass vial for two years.

Until the conditions under which organic materials are naturally carbonized are known, it cannot be assumed that all black plant fragments in pollen preparations are charcoal, although it is likely that most are. To be correct, the term "carbonized particle" should be used instead of "charcoal particle", but the latter is retained in this thesis because of the brevity of the term and the likelihood that the carbonized particles studied are charcoal.

Pollen preparation procedures will remove most objects likely to be confused with charcoal, but can they create black particles? The processing is designed to remove or bleach all but the most resistant organic materials. Acetolysis appears to darken plant fragments in pollen preparations but, used for an extended time (1-2 hours) to separate cuticle from fresh, dried or partly decayed plant material, does not blacken plant fragments and usually bleaches them. Corlett (1979) found that no black particles were produced from unburned plant materials by either a standard pollen preparation procedure, including acetolysis, or treatment for one hour in boiling concentrated nitric acid. Swain (1973) also found only colourless tissues after unburned plant fragments were given the same nitric acid treatment. It is most unlikely, therefore, that any black particles are created during sample preparation.

Effects of sample preparation on fresh charcoal

If comparisons are to be made between the amount of charcoal in different sediment types within or between sites, where different processing might be used, it is important to know what effects the preparation procedure might have. This has been tested as described below.

A mixture of wood and grass charcoal, collected after a forest fire, was crushed and wet sieved through standard brass mesh sieves. The fraction which passed through 63μm mesh and was retained on 44μm mesh was kept in suspension in water by a magnetic stirrer. Subsamples of 2ml were pipetted from the charcoal suspension and processed in 20 different ways; four samples were used for each treatment and eight (the four first and four last) were left untreated as controls. Two samples from one treatment (N) were lost in the final centrifuging. Table 2.1 summarizes the processing applied to each set of four samples. Details of each step are given in the pollen preparation procedure above, with the addition of the following:

12. Centrifugation

Centrifuged for 1 minute at 3000 rpm, decanted (twice).

13. Stirring

Two minutes on vortex stirrer.

14. Ultrasound

30 seconds in ultrasonic bath.

15. Ultrasound (30 sec) plus centrifugation (1500 rpm).

30 seconds in ultrasonic bath.

Centrifuged for 1 minute at 1500 rpm, decanted.

16. Ultrasound (10 sec) plus centrifugation (3000 rpm)

10 seconds in ultrasonic bath.

Centrifuged for 1 minute at 3000 rpm, decanted.

17. Control

No treatment

In order to separate possible physical and chemical effects on charcoal, the vortex stirrer and ultrasonic bath were used only where specified in this experiment.

Table 2.1: Procedural steps in preparation of charcoal samples; see text for details. Four samples were used for each treatment except where indicated.

Procedure number in text	Treatment	A[a]	B	C	D	E	F	G	H	I	J	K	L	M	N[b]	O	P	Q	R[c]	S	T
1	HCl (30min)							x													
2	HF/HCl (Hot,1h)								x					x	x	x	x	x	x		
3	KOH (2min)									x				x	x	x	x	x	x		
5	$ZnBr_2$/HCl										x				x	x	x		x		
6	Acetolysis (15min)											x				x	x	x	x		
7	$NaClO_3$ (15sec)												x				x				
10	HNO_3																			x	
11	Schulze																				x
12	Centrifugation		x																		
13	Stirring			x															x		
14	Ultrasound (30sec)				x																
15	Ultrasound (30sec) + centrifugation (1500rpm)					x													x		
16	Ultrasound (10sec) + centrifugation (3000rpm)						x														
17	Control	x																			

Notes: a - 8 samples, the four first and four last.
b - 2 samples only.
c - vortex stirrer used 30 times for 1-5 sec; ultrasonic bath used 3 times for 10 sec with centrifuging at 1500rpm.

Following treatment, the samples were resuspended in water, if necessary, and collected on 50mm diameter Sartorius cellulose nitrate membrane filters (type SM11342) with a pore size of 5µm. Millipore filtration apparatus was used, with the filter clamped between a sample chamber above and a sintered glass support on an evacuating flask below. Suction was obtained with a small, hand-operated vacuum pump. The filters were oven-dried at 60°C for about an hour, then mounted under coverglasses on slides with immersion oil. The slides were left overnight to distribute the immersion oil evenly and to drain any excess onto paper towels, then the overhanging edges of the filters were trimmed off with a razor blade. Filters were labelled with a blue Staedtler Lumocolor 317 permanent overhead projection pen, the only pen found whose ink is not affected by water, many chemicals or solvents or, over a day or two, by immersion oil.

Particles collected on membrane filters from suspension in this way are distributed evenly and randomly, and retained on the surface, rather than within the pores of the filter. Oven-drying ensures that particles do not move when immersion oil is added. The immersion oil (Zeiss 518C, n = 1.515) is of similar refractive index to the filters (n = 1.50-1.51), which are therefore cleared, allowing the use of transmitted light microscope illumination. As the particles remain on the surface of the filters, rather than being suspended between slide and coverglass, the distance required to focus through is minimized, which makes quantification of any objects with a microscope faster and less tiring. As well, particles are preferentially oriented with their largest surface parallel with the plane of the slide, which eliminates orientation as a source of variation between samples.

The total area of charcoal in each sample was estimated using the point counting technique (Chapter 3.1), sufficient points (N) being applied to each sample so that the relative standard deviation (s_p/P) was less than 5%. The area of each sample on the filters was $972mm^2$, so an estimate of the total area of charcoal in each sample was $972.P\ mm^2$ and of the 95% confidence limits was $972(P \pm 2s_p)\ mm^2$. The total number of charcoal particles in each sample was estimated roughly by counting all particles of area greater than $6\mu m^2$ (the minimum size a point could be seen to "touch") encountered on a transect 20 eyepiece micrometer divisions wide (0.11mm). Particles overlapping the left edge of the transect were included and those across the right edge excluded; the few which overlapped both sides of the transect were included. Counting continued until either a total of 1000 particles was reached or at least one transect across the slide (22mm) was completed, with a minimum count of 300 particles. An estimate of the total number of charcoal particles in each sample was calculated from:

(Area of sample on filter)(Number counted)/Area traversed in count.

The estimated mean particle area was then the ratio of the total area of charcoal to the total number of particles.

Estimates of the amount of charcoal in the samples are subject to two kinds of errors: experimental errors, such as variations in original sample size, and estimation errors, such as those arising from point sampling. While errors can be calculated for the point count estimates of area, the experimental error remains unknown. Any estimate of the area (a) of charcoal in a sample can be represented by:

$$a = \mu + e + s,$$

where μ is the unknown true area of charcoal, e is the unknown experimental error which is assumed to be normally distributed with mean zero and unknown variance σ^2, and s is the error of the point count estimate, also assumed to be normally distributed, with mean zero and known variance S^2(<u>cf</u>., Wilson and Ward, 1981).

For each treatment, or group of n samples, maximum likelihood estimates, $\hat{\mu}$ and $\hat{\sigma}^2$, of the true mean (μ) and variance due to experimental error (σ^2) can be obtained by solving iteratively the simultaneous equations (Wilson and Ward, 1981, p.34):

$$\hat{\mu} = (\Sigma a/(\hat{\sigma}^2 + S^2)/(\Sigma 1/(\hat{\sigma}^2 + S^2))$$

$$\Sigma 1/(\hat{\sigma}^2 + S^2) = \Sigma (a - \hat{\mu})^2/(\hat{\sigma}^2 + S^2)^2.$$

An estimate of the variance for the estimate of the mean of each group of samples is:

$$V(\hat{\mu}) = (\Sigma\ 1/(\hat{\sigma}^2 + S^2))^{-1},$$

and the standard error, or standard deviation of the estimate of the mean of each group of samples is:

$$SE(\hat{\mu}) = \sqrt{V(\hat{\mu})}.$$

Since n is not large, it is better to use the t-distribution rather than the normal for calculating 95% confidence limits. The limits are:

$$L = \hat{\mu} \pm t.SE(\hat{\mu}),$$

where the value of t is determined for (n-1) degrees of freedom and probability 0.05 (two-tailed).

For the estimates of the number of particles in each sample, there are no estimates of error due to a particular source. In the terminology used above, any estimate of the number (c) of charcoal particles in a sample can be represented by :

$$c = \theta + f,$$

where θ is the unknown true number of charcoal particles and f is the unknown error which is assumed to be normally distributed with mean zero and variance F^2. Assuming that the estimates of number within each sample group are normally distributed, the estimated mean $\hat{\theta}$, variance $\hat{F}^2$, standard error $SE(\hat{\theta})$ and 95% confidence limits may be calculated conventionally:

$$\hat{\theta} = (\Sigma\ c)/n,$$

$$\hat{F}^2 = (\Sigma (c - \hat{\theta})^2)/(n-1),$$

$$SE(\hat{\theta}) = \sqrt{\hat{F}^2/n},$$

$$L = \hat{\theta} \pm t.SE(\hat{\theta}),$$

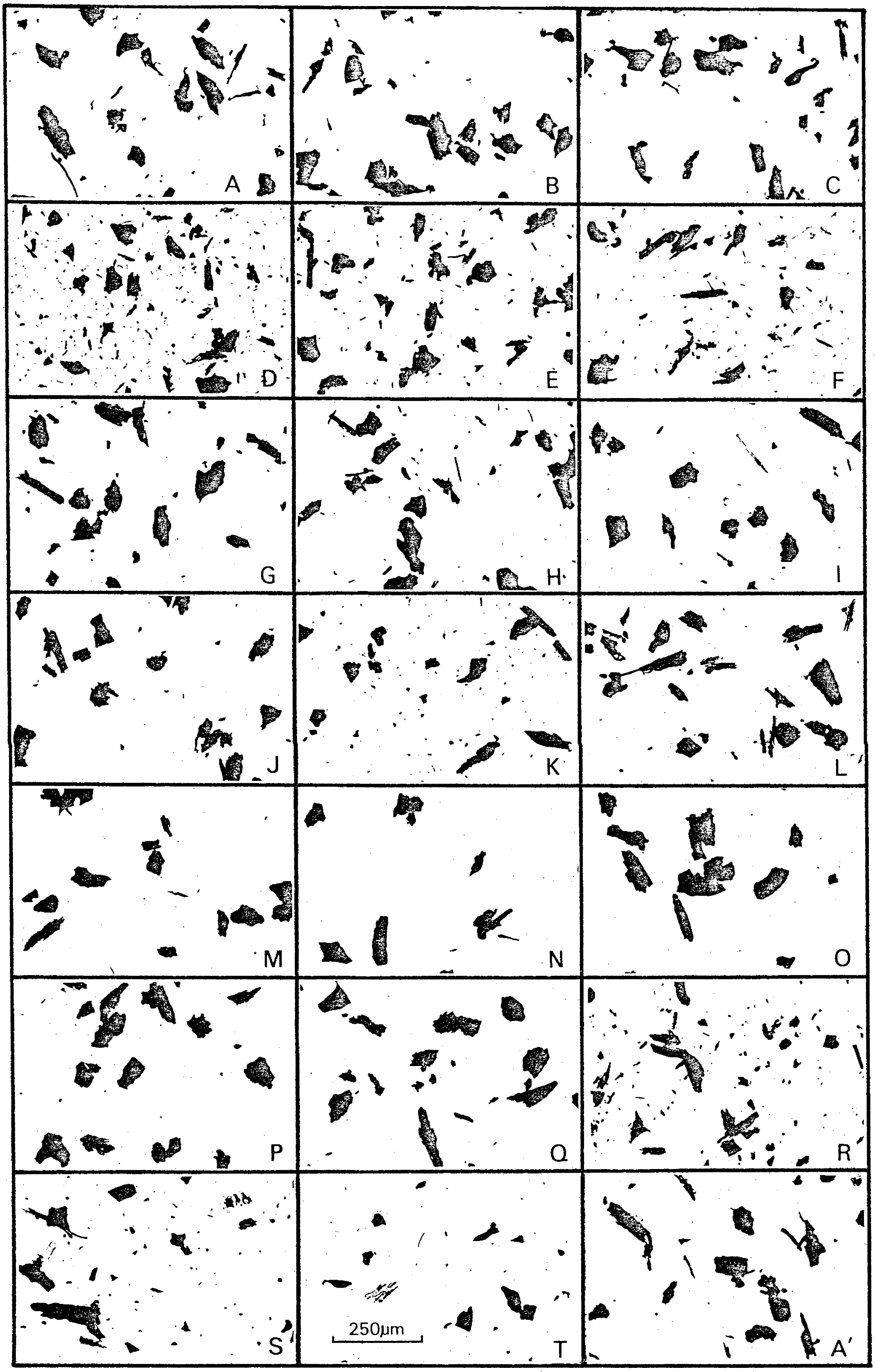
where t is determined for (n-1) degrees of freedom and probability 0.05 (two-tailed).

Figure 2.1 shows a typical field of view from each of the twenty treatments, Figure 2.2 presents the means and 95% confidence intervals of the area and number estimates and Figure 2.3 shows the relationship between area and number and changes in mean particle size for each treatment.

It is evident that only vigorous physical treatment increased the total area or number of particles, an increase which was not significant after 2 minutes on a vortex stirrer (treatment C), but highly significant after 30 seconds in an ultrasonic bath (D). The ultrasonic bath broke up charcoal particles, while subsequent centrifuging and decanting removed many of the smallest ones. Centrifuging at 1500 rpm (E) allowed more particles to be decanted than that at 3000 rpm (F). Centrifuging and decanting alone (B) reduced, but not significantly, the area and number of particles, some smaller particles being lost. Over all treatments, there was no correlation between the number of centrifugations and reduction in charcoal; such losses are obviously minimal.

Of the chemical treatments, hydrochloric acid (G) removed smaller particles, but did not make a significant difference to the total area. The other pollen processing steps taken individually (H-L) all significantly reduced the area of charcoal by about the same amount. Numbers were not reduced in hydrofluoric acid (H) or acetolysis (K),

Figure 2.1. A typical field of view of fresh charcoal after processing with each treatment B to T. See Table 2.1 for details. Controls, A and A', are untreated samples taken at the beginning and end, respectively, of the experiment. All are at the same magnification.


A
B
C
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L
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250μm
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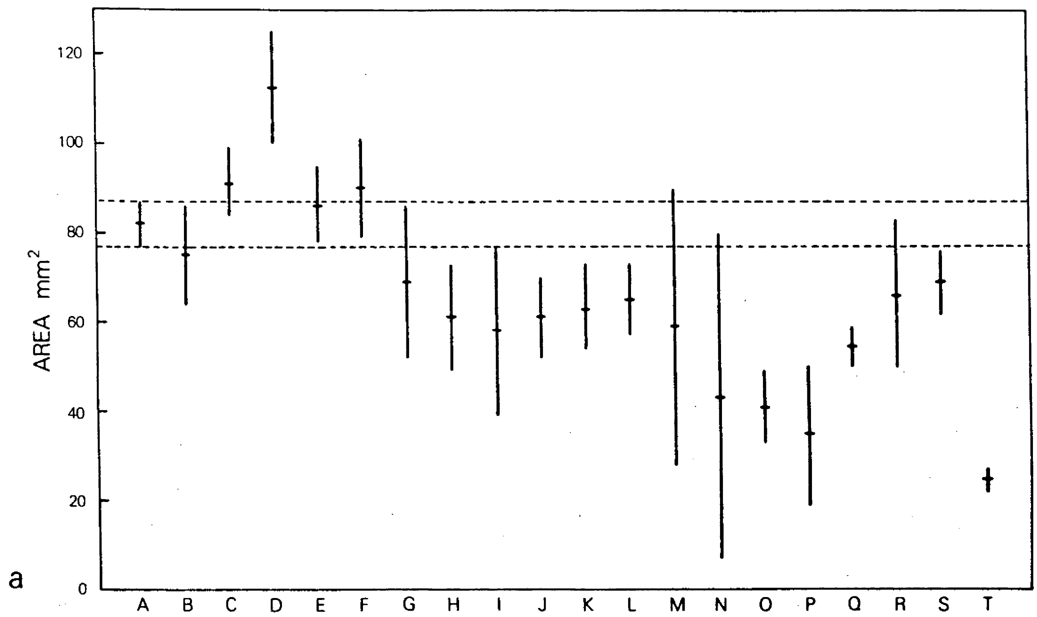


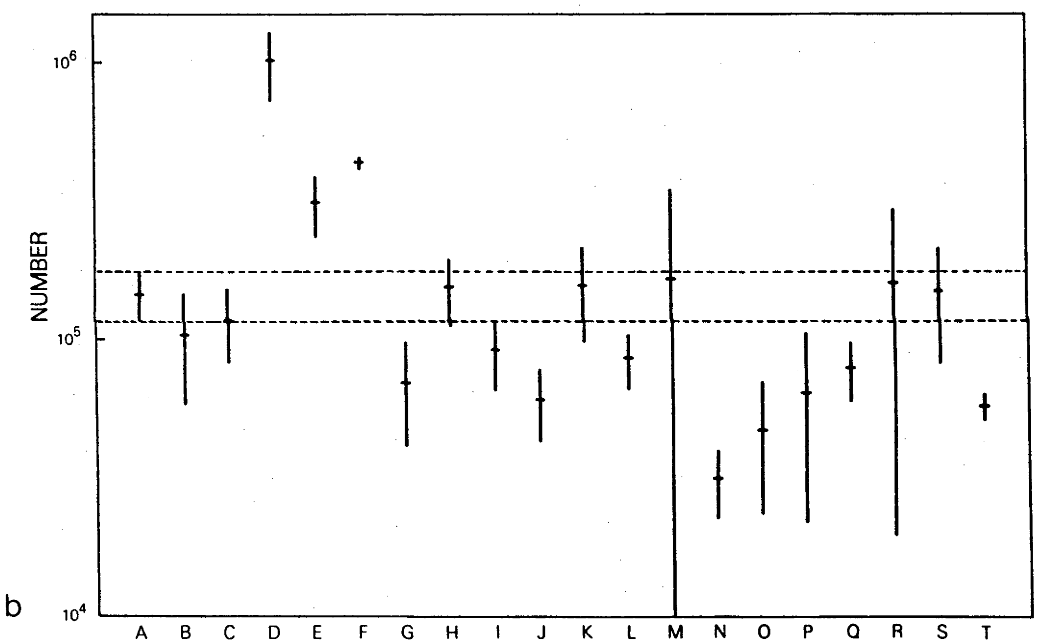
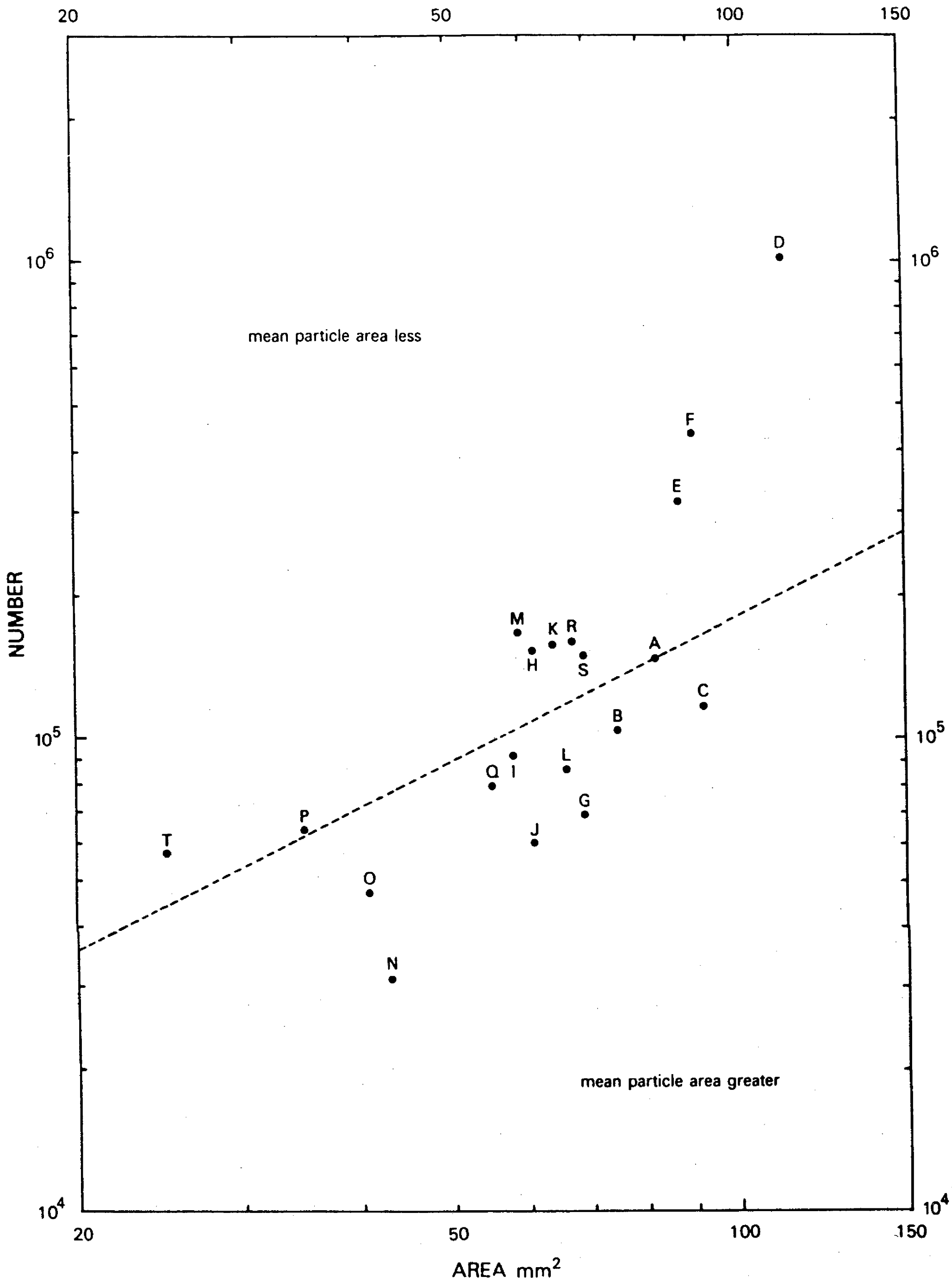


Figure 2.2. The effects on area of charcoal (a) and number of particles (b) of each treatment (A to T). See Table 2.1 for details. Means of samples in each group are represented by horizontal lines and 95% confidence intervals by vertical lines. The two dashed lines represent the 95% confidence limits of the controls (A).



<u>Figure 2.3</u>. The relationship between the mean area of charcoal and the mean number of particles in each treatment group (A to T) plotted on logarithmic scales. See Table 2.1 for details of processing. Treatments above the line have reduced the mean particle size from that of the control group (A); those below the line have increased mean particle size.

suggesting that these treatments broke up particles as well as removing some. Potassium hydroxide (I), zinc bromide (J) and sodium chlorate (L) all removed smaller particles, while sodium chlorate also bleached some of the grass charcoal, leaving it pale brown and indistinguishable from unburnt organic matter.

It is apparent from the treatments involving two or more steps in the usual pollen preparation sequence (M-Q) that only zinc bromide (N, O and P) makes a significant further reduction in the area of charcoal or the number of particles; the other steps do not augment the initial reduction. The physical losses of the density separation procedure are added to the chemical effects of the other steps. These losses could occur by particles being left in the top of the zinc bromide solution when floating organics are pipetted off or by inadequate dilution of the zinc bromide solution remaining with the organic fraction in the subsequent centrifugation. This result suggests that pollen, particularly the smaller grains, may also be lost in the density separation step unless extreme care is taken.

Decreases in the area of charcoal and the number of particles due to the pollen processing steps may be partly reversed by the use of a vortex stirrer and an ultrasonic bath (R). The opposing effects of the physical breaking-up of particles and their chemical or physical removal almost cancel each other, and there is no significant difference in area or number between the control samples (A) and those given the full chemical and physical processing (R), although the particle size distribution appears to have changed (Figure 2.1.R).

Hot concentrated nitric acid (S) broke up and removed some of the particles, but had no greater effect than the other chemical treatments. The strongest oxidant used, Schulze solution (T), had the most marked effect, both breaking up and removing many particles.

Effects of sample preparation on fossil charcoal

Does processing affect fossil charcoal as it does fresh charcoal? This will depend on the physical and chemical environments of the charcoal both during transport and after deposition, as well as the original degree of carbonization. The experiment described above is difficult to duplicate with fossil charcoal from sediments because of uncertainty in the identification of untreated black particles as charcoal, but some comparisons have been made.

Swain (1973) compared the amount of charcoal in 8 samples of sediments laid down between 1890 and 1970 and prepared in two ways:

(a) one hour in hot concentrated nitric acid; and

(b) a standard pollen preparation procedure, apparently consisting of the potassium hydroxide, hydrochloric acid, hydrofluoric acid and acetolysis steps.

He found the results to be "remarkably similar" (Swain, 1973, p.390). The nitric acid treatment (S) used in the experiment described in this chapter was for 10 minutes only and did not reduce the amount of charcoal as much as the pollen preparation procedure (Q) equivalent to Swain's. In Swain's experiment either both processes reduced the area of charcoal to the same extent or neither affected it; the former seems more likely from the evidence presented here. Corlett (1979) repeated this experiment on samples from New Guinea and found no significant differences in the charcoal content of samples prepared either way, or those given both treatments.

A similar experiment was performed on fossil samples from Lashmar's Lagoon (Chapter 7.1). Sub-samples of sediment from four levels between 310cm and 370cm (ca. 2500-3000BP) were treated in one of two ways:

(a) the hydrofluoric acid, sodium hydroxide, acetolysis and zinc bromide steps of the pollen preparation procedure, with the use of an ultrasonic bath for two bursts of about 30 seconds each; or

(b) a similar procedure to the above, but replacing the sodium hydroxide and acetolysis steps with 30 minutes in concentrated nitric acid in a boiling water bath, the sample being left overnight in the acid, then 5 minutes in hot 5% ammonium hydroxide solution.

The area of charcoal on each slide was estimated using the point counting method (Chapter 3.1), counting continuing until at least 2000 points had been applied. The number of particles on each slide was estimated by counting all particles with a maximum dimension >17μm on every tenth transect across the slide, using a x25 objective.

Results are presented in Figure 2.4 and it is evident that the long nitric acid treatment significantly reduced both the area of charcoal in each sample and the number of particles. Although the amount of charcoal has been reduced by the nitric acid treatment, the relativities between samples are maintained and would lead to the same interpretation. It is only when comparisons are made between samples prepared differently that the effects of the processing itself need to be taken into account.

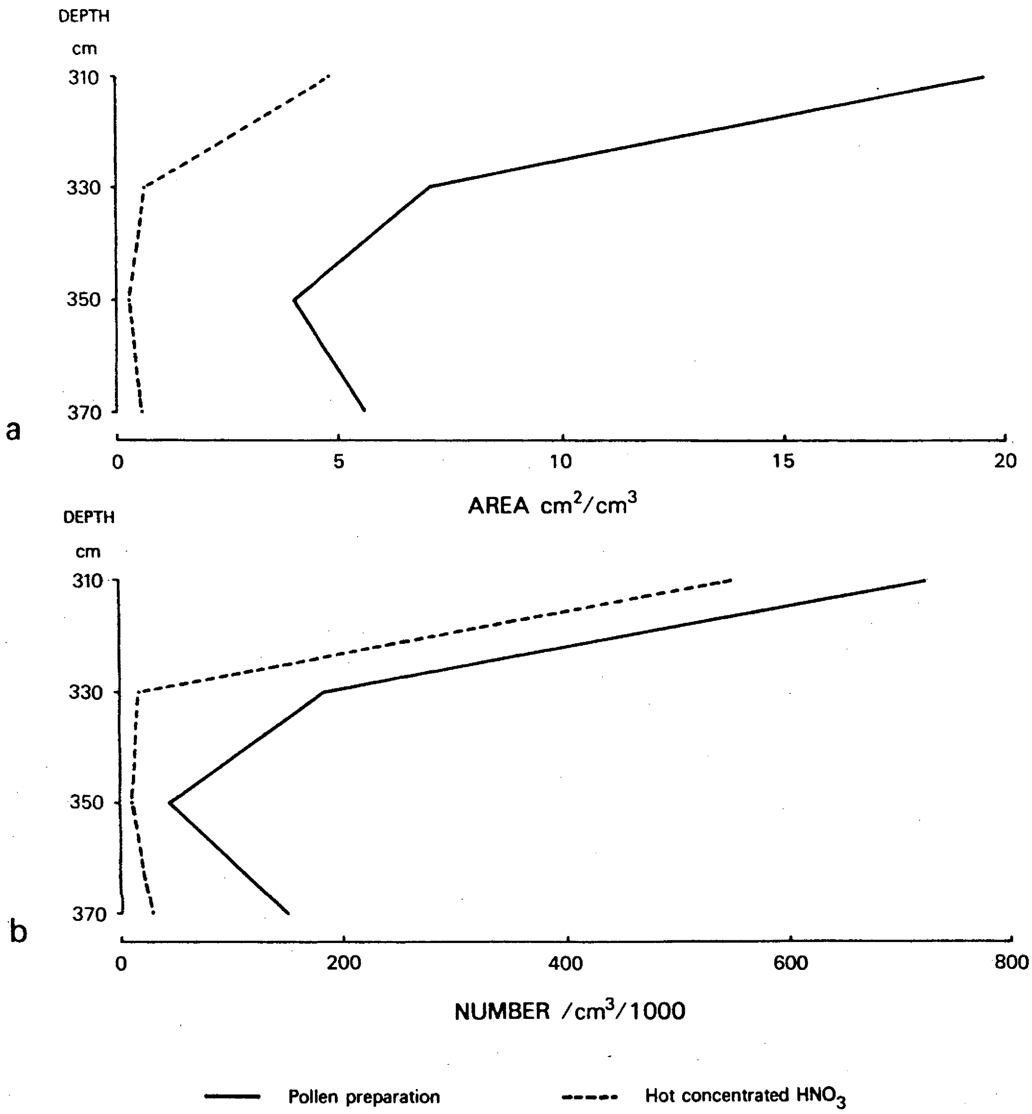


Figure 2.4. The relative effects of pollen processing (solid lines) and hot concentrated nitric acid treatment (dashed lines) on the area of fossil charcoal (a) and the number of charcoal particles (b) in samples from four levels of a Lashmar's Lagoon core. See text for details.

The nitric acid treatment has been recommended by Singh (Singh, Kershaw and Clark, 1981) to verify the identification of charcoal on the assumption that charcoal would be resistant to this treatment while other dark organic remains would be removed. As has been demonstrated, nitric acid also removes some of the charcoal, the amount lost depending on the time the sample is in nitric acid and the original degree of carbonization of the charcoal. With fossil samples it is impossible to determine how much of the dark material removed by this treatment might have been charcoal.

To test the effects on fossil charcoal of the use of an ultrasonic bath, three samples of equal weight from the same level of a sediment core (Didwana, 220cm, ca. 5000-6000BP; Singh, pers. comm.) were processed for pollen analysis using the hydrofluoric acid, sodium hydroxide and zinc bromide steps. One sample was given no treatment in the ultrasonic bath, one had standard ultrasonic treatment (two bursts of about 30 seconds each followed by centrifuging at 1500 rpm and decanting) and the third was left in the ultrasonic bath for about 30 minutes before being centrifuged and decanted. After processing, the samples were kept suspended in 40ml of water by a magnetic stirrer and two 1ml subsamples pipetted from each. The subsamples were collected on membrane filters and the area and number of charcoal particles estimated as described earlier in this chapter. The means of the results from each treatment are presented in Table 2.2. It is evident that the short treatment in an ultrasonic bath has broken up the charcoal, in this case mostly from grass, and the subsequent centrifuging and decanting have removed some of the smaller particles. The very long treatment has an even more marked effect. If ultrasonic treatment is required for one or more samples from a site, then all samples from that site should be treated equally and the use of an ultrasonic bath recorded as part of the preparation procedure.

Table 2.2. The effects on fossil charcoal content of different times in an ultrasonic bath. Samples of equal weight were processed as described in the text. The amount of charcoal is that in 1ml subsamples of suspensions of processed samples in 40ml of water.

Time in ultrasonic bath	Amount of charcoal		
	Area mm^2	Number	Mean particle area: μm^2
0	100	788,000	127
2 x 30 sec	85	938,000	90
30 min	71	1,453,000	50

As all processing affects the amount of charcoal, some steps, singly or in combination, more than others, it is recommended that all samples from one site are prepared identically. This eliminates one variable, but not differential responses to processing of charcoal of varying degrees of carbonization. Quantitative comparisons must be made with care where different processing has been used. The use of strong oxidants, which remove an unknown amount of charcoal, should be avoided except where necessary to eliminate insect cuticles or sulphide crystals. On the other hand, if only charcoal is being analysed and not pollen or other microfossils, preparation of the sample by treating it for 1 hour in hot concentrated nitric acid is probably simplest and removes most other confusing material. Most often, charcoal is analysed with pollen to reconstruct vegetation and fire histories. The use of the same preparations for pollen and charcoal analyses saves time and the standard pollen preparation procedures remove most particles which could be confused with charcoal.

Chapter 3

QUANTIFICATION OF CHARCOAL

No one method for quantifying the charcoal content of pollen preparations has yet been adopted universally. The two methods most often used have been to count numbers of charcoal particles or to measure their areas by means of a grid of squares of known size in the microscope eyepiece. Size distributions may be determined from the area measurements of individual particles or, more rapidly, by measuring the maximum dimension of each particle. Both number and area may be expressed as a percentage of the pollen sum or as a ratio to total pollen content (e.g., Swain, 1973; Hope & Peterson, 1976; Amundson & Wright, 1979), as total content per unit volume of sediment (e.g., Davis, 1967; Mehringer, et al., 1977; Singh, Kershaw and Clark, 1981) and, most usefully, in suitable cases, as influx per unit area per year (e.g., Byrne, et al., 1977; Green, 1981; K. Tolonen, in press).

A simplified procedure for area size-classing has been developed by E.J. Cushing (pers. comm.). The microscope image of a charcoal fragment is compared with a standard diagram of different sizes of charcoal particles relative to the diameter of the field of view and to the size of inert microspheres included in the sample. Iversen (1941) determined relative frequencies of charcoal particles by counting the number of particles crossed by a ten centimetre line. In his later work (Iversen, 1964, 1969), he used a point counting procedure similar to that described in this chapter to determine the area of charcoal and other constituents of the pollen preparations, but the results were given as percentages of the area of pollen, which itself was adjusted to 100% for each sample, assuming constant pollen deposition and preservation. Singh (Singh, Kershaw and Clark, 1981) uses an analogous procedure that does not estimate area, so results are expressed as surface area ratios per unit volume of sediment.

Provided that all samples are prepared in the same way and only large changes in charcoal content are considered significant, all these methods appear to be satisfactory in providing estimates of relative charcoal quantities, but point counting is recommended as it is easy to use and takes the shortest time to obtain results of a given accuracy. In practice, it takes 10-30 minutes to estimate the area of charcoal in a pollen preparation by the point count method, as against 1-3 hours using a square eyepiece grid. If there are very few charcoal particles in a sample, then it is simpler and faster to count numbers.

3.1 Point counting

Sampling theory

Glagoleff (1933) first showed that by applying a number of points to a plane surface, the ratio of the number of points (C) intercepting a particular phase within that surface to the total number of points (N) measured the areal density (A_A) of that phase, areal density being the ratio of the area of the phase (A) to the area of the plane (A_p). The area of the phase (A) could then be estimated from the total area of the plane surface (A_p):

$$A = A_A.A_p = A_p.C/N.$$

More generally, the probability (P) of any point applied at random on a plane surface intercepting a particular phase will be the ratio of the area of the phase to the total area of the plane:

$$P = A/A_p = A_A ,$$

and, for estimation,

$$P = C/N.$$

Applying N test points at random on a plane surface is equivalent to making N independent trials, each of which has two possible outcomes - a point intercepts or does not intercept a particular phase - with probabilities of, respectively, P and (1-P). In samples of N test points, the number of points (C) touching a particular phase will have a binomial distribution, so the standard deviation of C is:

$$s_C = \sqrt{N.P(1-P)},$$

the standard deviation of the probability (P) is:

$$s_p = \sqrt{P(1-P)/N},$$

and the standard deviation of the estimated area of the phase (A) is:

$$s_A = A_p. \sqrt{P(1-P)/N}.$$

The accuracy, or relative error (s_p/P), of the estimate will obviously improve with the number of points applied and may be calculated in one step:

$$(s_p/P) = \sqrt{(1-P)/C}.$$

The number of points (N) required to achieve a given relative error (s_p/P) may also be estimated:

$$N = (1-P)/P(s_p/P)^2.$$

If N is large (>1000), the binomial distribution approaches the normal and 95% confidence limits lie at approximately $A \pm 2s_A$. Note that these estimates apply only to the statistical errors of the procedure and take no account of sampling or experimental errors.

It is immaterial whether the points are applied randomly or in any pattern, as long as such a pattern does not conform with one in the specimen itself. Hilliard and Cahn (1961) have shown that a two-dimensional systematic point count, that is, the use of a regular grid of points, is not only faster than a random point count but produces a statistically more accurate estimate for the same number of points. They show this is true if there is no periodicity in the structure being studied, if the grid is applied randomly or systematically to the sample and if the spacing of the points is such that the majority of the features being measured are not touched by more than one point.

Delesse (1847) demonstrated that the area of each constituent on a random section through a rock is exactly proportional to its volume in that rock. That is, volume density (V_V) is equal to areal density (A_A) and the volume of a particular phase (V_c) in a total volume (V) may be estimated by a point count on random sections:

$$V_V = A_A = C/N,$$

$$V_c = V.V_V = V.C/N.$$

This relationship has been fundamental to the development of quantitative microscopy and stereology. Full accounts of the methods, assumptions and proofs based on probability may be found in DeHoff and Rhines (1968), Underwood (1970) and Weibel (1979, 1980). Miles and Davy (1976) and Davy and Miles (1977) present a more general theory based on geometric probability and integral geometry from which the stereological formulae are derived.

In pollen preparations on microscope slides, there is a non-random orientation of contained particles, which usually lie flat on the plane of the slide, and particles may overlap. Therefore, any estimate of the area of those particles will be of maximum projected area, from which volume cannot be directly extrapolated.

Point count estimates of charcoal area in pollen preparations.

As discussed above, a systematic two-dimensional point count is the most efficient way of estimating the area of a phase in a plane surface. Use of the method to estimate the projected area of charcoal (the phase) on a microscope slide (the plane surface) gives only the total area, without numbers of particles or size-classing.

On a microscope, an appropriate grid may be obtained by using an eyepiece reticle with an array of points and moving the field of view on transects across the slide. The points in the eyepiece reticle may be defined by the intersections of lines or the ends of lines; the latter are easier to use as there is less masking of the features under consideration. If a reticle specifically designed for point counting (Weibel, 1979, 1980) is not available, the ends of lines on an eyepiece micrometer (see Figure 3.1) are quite satisfactory for defining points. The distance between points on the reticle and the magnification used should be chosen so that only one point falls on the majority of individual particles. For speed and comfort, it should be possible for all points on the reticle to be taken in at a glance; the actual number of points will depend on their arrangement and distance apart and on the density of the preparation. If there are few particles dispersed in a clear matrix a larger number of points may be used, but if the density of the particles is high or if there is a high concentration of organic remains in the matrix, then it is easier to use fewer points. The number may vary from, say, five to fifteen. The transects across the slide may be chosen randomly or, more rapidly, by a predetermined pattern using a calibrated stage. For example, parallel transects may be spaced every three millimetres along the slide. As pollen preparations are usually not dispersed evenly over slides, it is essential to have more transects with fewer

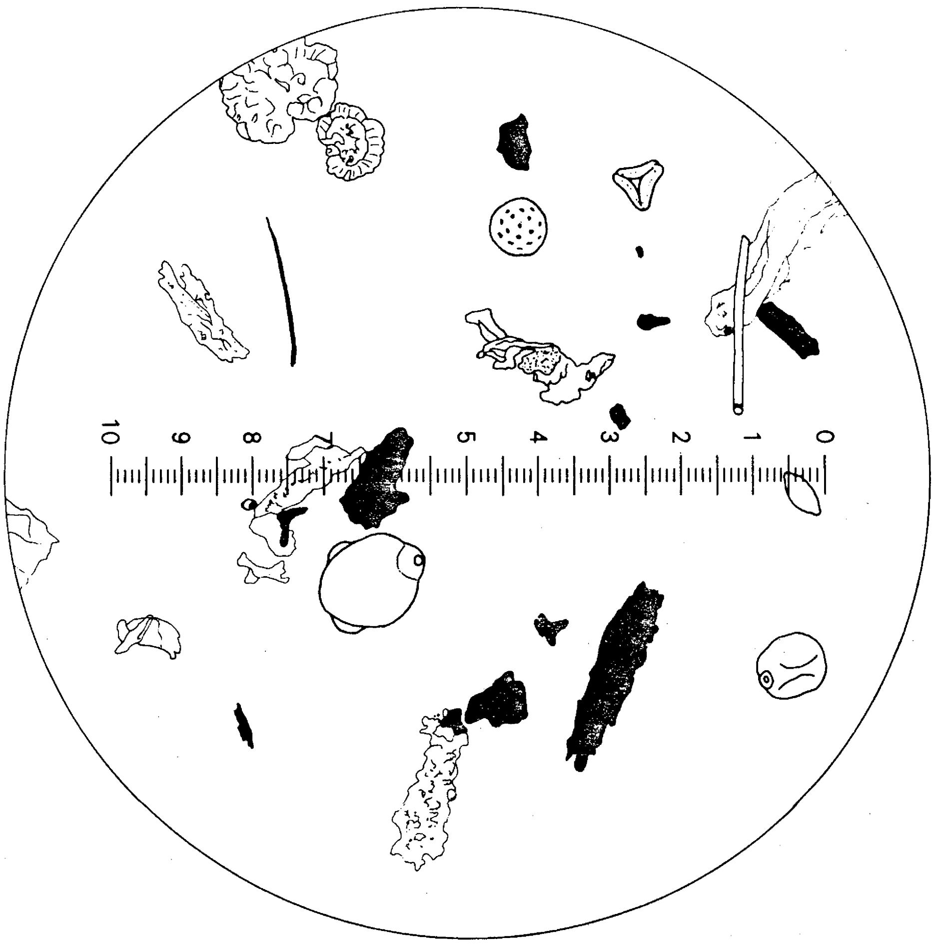


Figure 3.1. A field of view in a pollen preparation with a standard eyepiece micrometer. Of the eleven points defined by the upper ends of lines nearest the numbers, only one "touches" charcoal. If the preparation was more dense, fewer points could be used, *e.g.*, those numbered 3 to 7.

points in each, distributed over the entire sample area, rather than to apply a large number of points in a small and possibly unrepresentative area.

After the reticle, the points, the magnification and the spacing of the transects have been selected, the field of view is moved step by step along the transects by advancing the stage and a record kept of the number of fields of view and of points falling on charcoal. If a stage with an automatic advance is available, each of these steps may be made equal and of a predetermined distance. If not, the stage must be advanced manually, taking care not to bias the results by selecting the field of view. A mechanical tally counter is the simplest way of recording results. Devices are available with an automatic stage and a tally counter that calculates the percentage of points touching objects of interest (100.P). If there is doubt whether a point is touching the edge of a charcoal particle, one half should be scored, or every second such point counted. The total number of points applied may be calculated by multiplying the number of fields viewed by the number of points on the reticle. The area of charcoal on the slide is then estimated (see Appendix A). If the sample covers the entire area under the coverglass, then the sample area (A_p) is equal to the area of the coverglass. If the preparation has been sealed with wax under the coverglass, then the area of the sample may be estimated by applying a grid of points, such as graph paper, to the slide, or by using a planimeter. Where many samples are involved, the slides may be arranged on a sheet of photographic paper which is exposed under an enlarger. A planimeter connected to a computer may then be used to measure the area of the image of each sample, and results are stored for subsequent calculations. Estimating the area of the sample adds another step to the procedure, and more uncertainties; if wax preparations are preferred for pollen analysis, it may be simpler to make duplicate slides with the sample spread under the entire coverglass area.

The number of points to be applied will depend on the concentration of charcoal particles and the accuracy required. The number may be calculated using the formula in Appendix A or read off the curves in Figure 3.2. It is obvious that for low values of P, the effort required for greater accuracy may not be justified. This is particularly so with pollen preparations where the sampling errors may be large and small differences between samples not significant.

From the area of charcoal on the slide, an estimate may be made of the area of charcoal in a unit volume of sediment or the annual influx per unit area (see Appendix A). If the volume of the subsample on the slide is not known, but markers of exotic pollen grains or spores or microspheres have been added, it is necessary to estimate the number of markers on each slide. This may be calculated from the number recorded in the area traversed while counting pollen, or by recording the number of points which fall on marker grains or microspheres. The total area occupied by the markers may be calculated and their number determined by dividing this total area by the mean area of individual grains or spheres. If a relative, or percentage, pollen diagram is used, the area of charcoal relative to the pollen sum may be calculated from the area traversed in counting the pollen.

The recommended procedure, formulae to be used and a worked example are given in Appendix A.

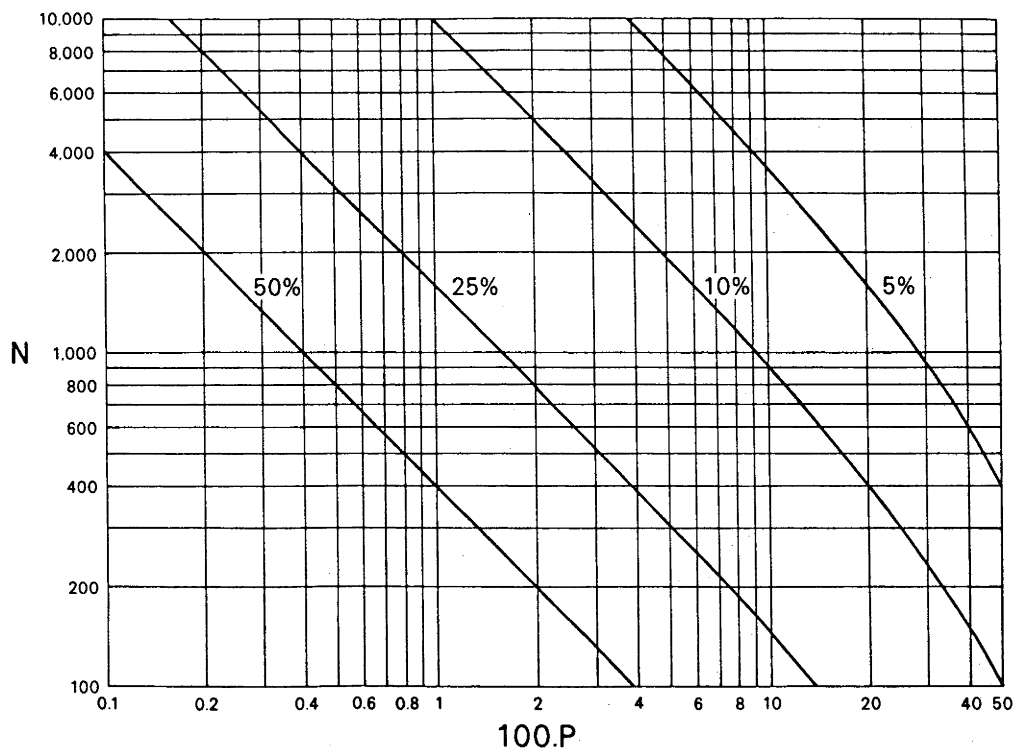


Figure 3.2. The number of points, N, required for relative errors, $(s_p/P)\%$, of 5%, 10%, 25% and 50% for values of P. N has been calculated using the formula: $N = (1-P)/P(s_p/P)^2$. To find the number of points required for an estimate of P, multiply P by 100 and read off the value of N for the intersection of 100.P with the curve for the required relative error. The graph may also be used to estimate the relative error from N and P.

Point count estimates of charcoal volume from thin sections.

Sediment samples can be impregnated with wax or plastic and thin sections prepared by cutting with a microtome or grinding and polishing (Tippett, 1964; Merkt, 1971; Saarnisto, et al., 1977). With the sections oriented at right-angles to the sediment surface and to deposition layers, a series of such sections can be made to cover the entire length of a core. A point count of charcoal, as described in the previous section, may be made on adjacent transects across the sections, parallel with the deposition plane, or at any selected interval. If the sediments are laminated, then the point count may be made on each lamina, giving annual or seasonal charcoal input. If no laminations are visible, counts may be made on transects whose distance apart is determined by the resolution required. Counts from successive transects may be combined to express the results from any given length of core at any interval, from the equivalent of each pollen sample or for specified time periods. The estimated volume of charcoal (V_c) per unit volume of sediment is then:

$$V_c = C/N,$$

where C is the number of points falling on charcoal and N the total number of points applied (see Sampling theory above). Errors are estimated as for the area calculations. If counts have been made for each year of annually laminated sediments, or if the number of years in the sample is known, then the annual input volume may be estimated.

It is essential for this procedure that random thin sections through the sediments be used; peels, such as those recommended by Simola (1977) and Terasmae and Weeks (1979) will remove whole particles. Peels are useful only for relative proportions of constituents as the volume adhering to the tape or slide will vary with the type of sediment, the size of its inclusions and the degree of compaction. Thin sections at right angles to the deposition plane do not provide a truly random section through the charcoal, as particles will be preferentially oriented lying flat on that plane. The estimate of area and volume from thin sections will thus be a minimum estimate of the quantity of charcoal, but comparable between levels and between sites. The main difficulty with the method is that, without chemical treatment of the sediment, such as pollen preparation procedures (see Chapter 2), dark organic or inorganic material other than charcoal is not removed. With some sediments this problem will not arise; with others, the charcoal content of pollen preparations can be compared with the black material in the thin sections to assess any difficulty with identification.

Examples

(a) Point count estimation of area.

To check the accuracy of the point count method, a mixture of _Ambrosia_, _Juglans_ and _Pinus_ pollen suspended in silicone oil was mounted on a slide under a coverglass. A square was marked on the coverglass and the number counted of each type of pollen grain within the marked area. Grains partly outside the area on two adjacent sides of the square were included and those overlapping the opposite sides excluded. Using a reticle with a grid of squares of known size, the area was measured of each of thirty _Ambrosia_ and _Juglans_ grains and ten _Pinus_ grains. Means and standard deviations were calculated. The total area occupied by each pollen type was then estimated from the product of the number of grains and their mean area. A point count estimate was made of the total area of each of the three pollen types within the marked square, using a x10 objective and applying 2800 points. Standard deviations were calculated as described earlier in this chapter and in Appendix A. The time taken for the point count was a fraction of that required for the area measurements of individual grains and of that for counting numbers.

Results are presented in Table 3.1. There is no significant difference between the two estimates of area for any of the three types of pollen; the speed, ease and accuracy of point count estimation make it the preferred method.

Table 3.1. Estimates of the areas of three types of pollen grains in a pollen mixture, and of the standard deviations of the area estimates. See text for details.

	TOTAL AREA, mm^2	
	From number and mean area	From point count
Ambrosia	1.41 $\pm$ 0.174	1.53 $\pm$ 0.096
Juglans	0.52 $\pm$ 0.083	0.49 $\pm$ 0.056
Pinus	0.13 $\pm$ 0.019	0.14 $\pm$ 0.030

This data set comprises three variables: the total number of each pollen type, the total area of each and the mean area of individual grains. Any one of these may be calculated from the other two. In the comparison above, total area was calculated from mean area and total number. The total number can be calculated if the total area and mean area are known or estimated, and mean area can be derived from total area and number. Table 3.2 lists these calculations made with data from the pollen mixture; these provide examples for applications of point count estimation of area to a variety of problems. In all these results, accuracy would have been improved if more points had been counted.

Table 3.2. Comparisons of estimates of numbers and areas of pollen grains in a pollen mixture. Total area was estimated by point counting, mean area by estimation from individual grains. See text for details.

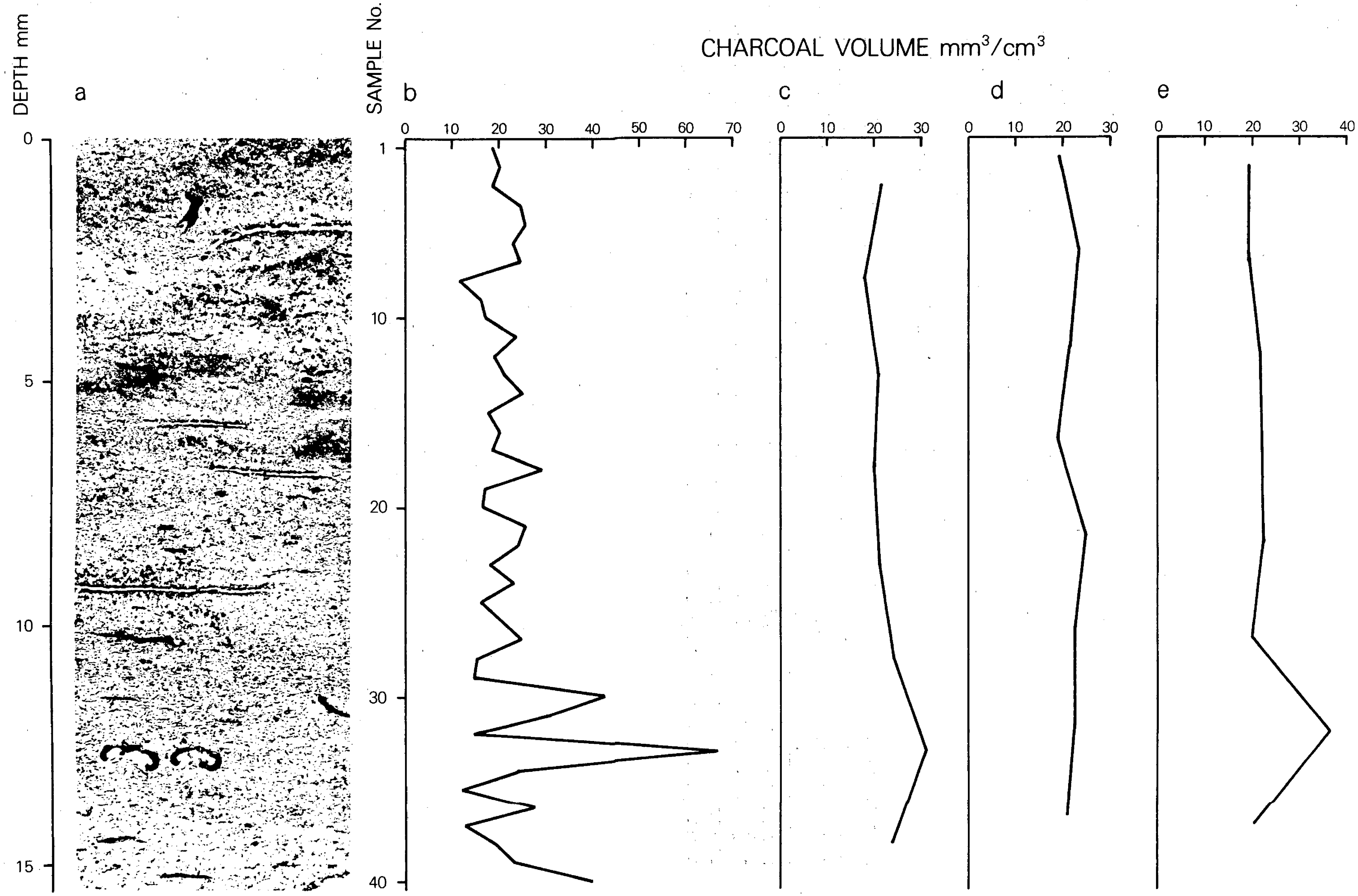
	Ambrosia	Juglans	Pinus
Number counted	4960	579	49
Number from: Total area/Mean area	5387	542	51
Mean area (μm^2)	284	901	2702
Mean area (μm^2) from: Total area/Number	308	846	2857

(b) Point count estimation of volume.

A thin section of sediment about 3000 years old from Lake Barrine in north-east Queensland (J. Owen, pers. comm.) was prepared by freeze-drying, impregnating with epoxy resin, polymerizing the resin and cutting, grinding and polishing (M. Campion, pers. comm.). Using a x25 objective, point count estimates were made of the amount of charcoal on 40 adjacent, 0.39μm wide transects parallel to the deposition plane. Where the section extended the full width of the coverglass (22mm), from 1722 to 2625 points were applied on each transect. The lowest transects (numbers 34 to 40) did not extend across the full width, so fewer points were counted. As the section was comparatively thick (*ca.* 45μm), one optical plane was used for the application of points. The proportion (P) of the area occupied by charcoal on each transect was estimated and from this, as shown earlier in this chapter, an estimate was made of the volume of charcoal in the sediment.

Figure 3.3 shows part of the thin section (a) and four charcoal curves constructed from the point count estimates of volume: (b) the complete curve for adjacent transects; (c) the same data lumped in groups of five contiguous transects; (d) two contiguous transects lumped, with three transects between each pair; and (e) three

Figure 3.3. (a) Part of a thin section of sediment from Lake Barrine. The volume of charcoal per unit volume of sediment was estimated by point counting on 40 contiguous, 0.39μm wide transects parallel to the deposition plane. Results are presented in four ways: (b) the complete curve for adjacent transects; (c) the same data lumped in adjacent groups of five contiguous transects; (d) two contiguous transects lumped, with three transects between; and (e) three contiguous transects lumped, with two transects between.



CHARCOAL VOLUME mm³/cm³
DEPTH mm
SAMPLE No.
a
b
c
d
e

contiguous transects lumped, with two transects between.

There is an excellent correspondence between the obvious charcoal in the thin section (Figure 3.3a) and the point count estimate of volume (Figure 3.3b). Using the point count method on thin sections, changes in the charcoal content of sediments can be determined in great detail, while estimates of volume of charcoal are more realistic than those of area or number and can be directly related to the amount of charcoal produced in fires and transported to sediments. Information is lost by sampling techniques which average several samples (Figure 3.3c) or sample at intervals (Figure 3.3d and e). This point will be discussed more fully in Chapter 6.

Other applications

The point counting methods described here may also be applied to constituents of the sediments other than charcoal, such as pollen, diatoms, phytoliths, fungal spores or mineral grains. Instead of a manual point count, an automatic image analyser could be used, if it is capable of discriminating between objects in the field of view. While this may be valuable on thin sections of sediments if great detail is required, for most purposes automated analysis appears, at present, more time-consuming.

Stereological techniques, including point counting, were developed initially for estimating the volumes of components of rocks (Delesse, 1847; Glagoleff, 1933), then used in the biological and medical sciences to make quantitative extrapolations to whole tissues or organs from thin sections (e.g., Weibel, 1973; W.L. Nicholson, 1978). The use of point quadrats for vegetation analyses was developed independently (e.g., Levy and Madden, 1933; Goodall, 1952, 1953). The point count method of estimating areas has been applied to a variety of problems in work described in this thesis. It has been used to estimate the area of fossil charcoal in pollen preparations (Chapter 7), of fresh charcoal in samples processed differently (Chapter 2) and of charcoal transported from fires and collected on sticky slides, rotating impactors or in water samples (Chapter 5). As well, the method was used to estimate the areas of the ground surface of a burned catchment covered by different features and the proportion of charcoal in litter samples (Chapter 5.5). Because the method is so simple and rapid, many more samples could be included than would otherwise have been possible.

3.2 Area or number?

The method of estimating the area of charcoal in pollen preparations by using an eyepiece grid of squares of known size, introduced by Waddington (1969), was adopted by others on the assumption that estimating area redressed the imbalance caused by giving equal weight to each particle, irrespective of size, when counting numbers. This method of estimating areas is far more time-consuming than counting numbers, while point count estimates of area take least time. An example given in the previous section showed that the two methods of estimating area produce comparable results (Table 3.1), but is there any relationship between number and area, or are they independent, as has been assumed?

In Figure 2.4 an example was given of the effects of different processing on the area of charcoal and the number of particles. It was pointed out that although the total quantities differed, relativities between samples were maintained. It is also apparent that estimating the total area of charcoal by point counting and counting the number of particles are equally satisfactory for

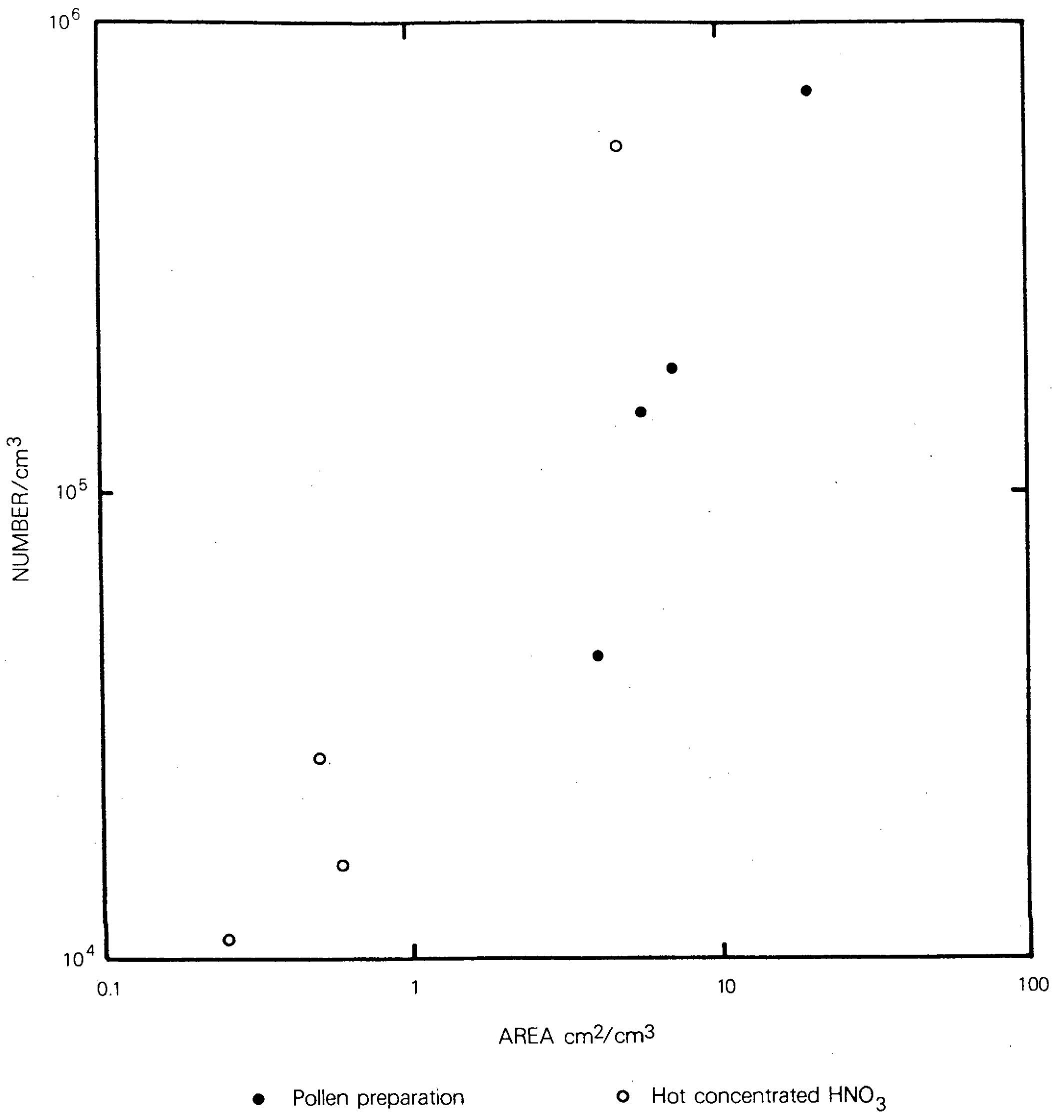


Figure 3.4. Lashmar's Lagoon data from Figure 2.4 redrawn, plotting total areas of charcoal against numbers of particles on logarithmic scales.

estimating relative amounts. The same data is redrawn in Figure 3.4, where number is plotted against area on logarithmic scales. Even with such a small sample, there is a good correlation between area and number, particularly for samples processed the same way.

Green (pers. comm.), analysing the charcoal content of cores from four eastern Canadian lakes, counted the number of particles in three area size classes with geometric means of 450µm^2, 4 x 450µm^2 and 16 x 450µm^2, using an eyepiece grid of squares. He then calculated the total area of charcoal in each sample and the annual influx, both in numbers and in area. Green's data for the cores from Everitt Lake (Green, 1976, 1981), Curry Pond, Collins Lake and Duck Lake (Green, 1976) are plotted on logarithmic scales in Figure 3.5 (D, E, F and G) and show significant correlations between area and number. A similar method was used by Amundson and Wright (1979) who published curves of both area and number of charcoal particles which show excellent correspondence.

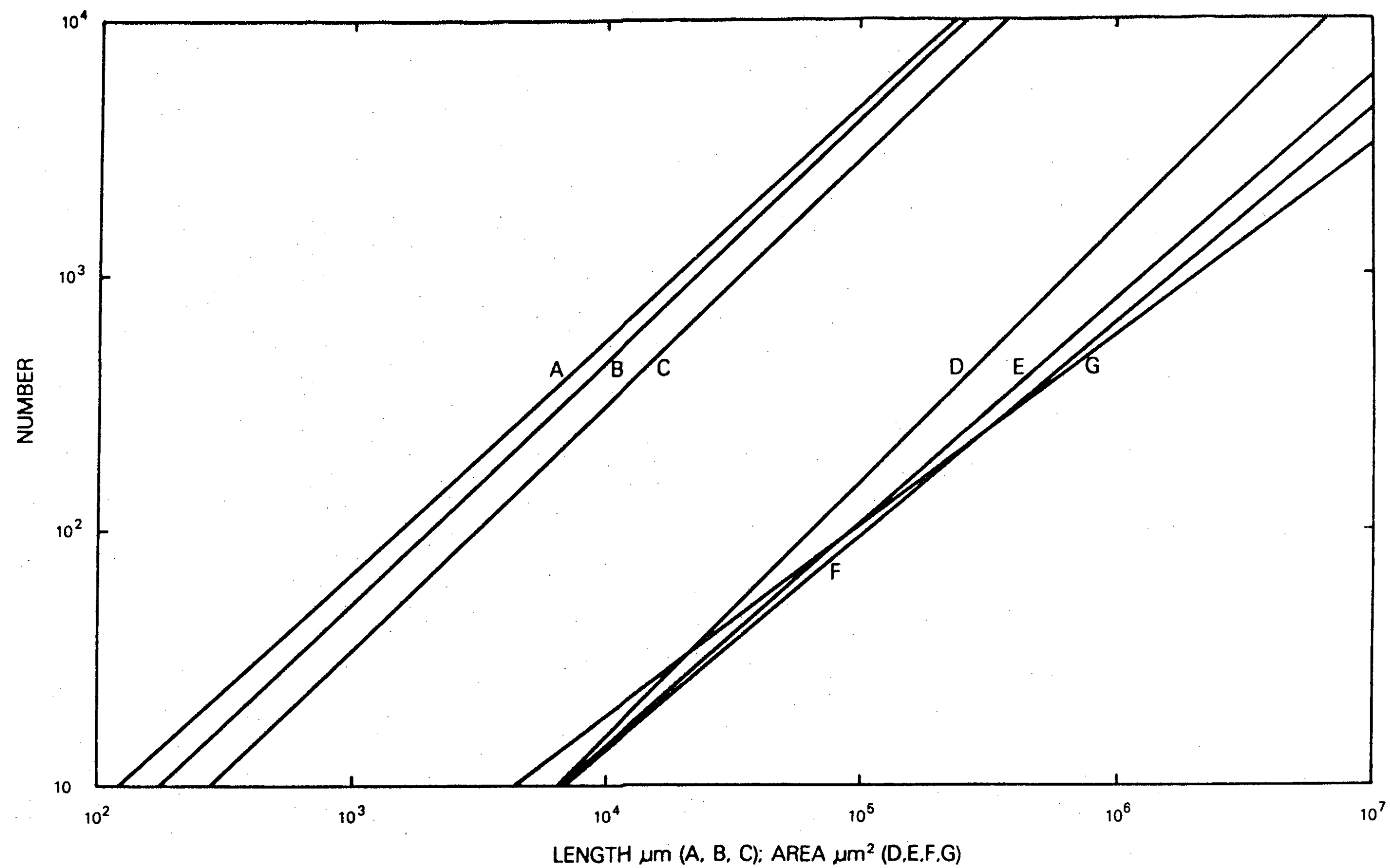
A method analogous to area size-classing has been applied to three sets of samples collected as described later in this thesis (Black Mountain: Chapter 5.2; Eden: Chapter 5.3; and Lashmar's Lagoon: Chapter 7.1). Instead of estimating the areas of individual particles, a more rapid method was used in which the maximum dimension of each particle was measured using a calibrated eyepiece micrometer scale (Figure 3.1). Numbers of particles were tallied in each of 15 length classes from 6.5µm to 104µm, with class divisions at 6.5µm intervals, this being the distance between eyepiece divisions at the magnification used. For the Lashmar's Lagoon samples, where the preparation was very dense, the lowest two size divisions were excluded. The total length of charcoal particles in each size class was then calculated from the number and mean length. As the width of each size class was relatively small, it made little difference whether the arithmetic or geometric mean was used. Numbers and lengths in all size classes were then added to give total numbers and total lengths for each sample. Although only one dimension is taken into account, length should provide a measure of size as valid as area, but subject to similar limitations. The relationship between total number and total length of charcoal particles in samples from the three sources is shown on logarithmic scales in Figure 3.5 (A, B and C). Within each set of samples there is excellent correlation between number and length.

It is apparent from the correlations between area or length of charcoal and the number of particles that, in samples from any one site or collection, the number of larger particles is proportional to the number of smaller. Where the slope of the regression between number and area or length of charcoal in samples from different sites is the same, the size distributions must be identical. Of the sites or collections plotted in Figure 3.5, B and C have similar size distributions, while D and G differ, with G having a greater proportion of larger particles. Differences in size distributions are also evident from the distances between regression lines for sites where the same size range has been used for analysis (A and B; D, E, F and G of Figure 3.5. If analyses of samples from site C had included the two smallest size classes, then the relationship between length and number for sites B and C would have been almost identical.).

Figure 3.5. Total length of charcoal (A,B,C) or area of charcoal (D,E,F,G) plotted against numbers of charcoal particles in all samples from seven sites.

A: Eden; number of samples (n) = 15, correlation coefficient (Pearson's r) = 0.9889, slope (b) = 0.9083.
B: Black Mountain; n = 119, r = 0.9784, b = 0.9428.
C: Lashmar's Lagoon; n = 4, r = 0.9996, b = 0.9602.
D: Everitt Lake, Nova Scotia; n = 173, r = 0.9457, b = 0.9919.
E: Curry Pond, Nova Scotia; n = 34, r = 0.9414, b = 0.8762.
F: Collins Lake, New Brunswick; n = 36, r = 0.9519, b = 0.8364.
G: Duck Lake, Nova Scotia; n = 13, r = 0.9246, b = 0.7479.

The two smallest size classes used for samples from sites A and B were not included in the estimates of samples from site C.



NUMBER
10⁴
10³
10²
10
A
B
C
D
E
F
G
10²
10³
10⁴
10⁵
10⁶
10⁷
LENGTH µm (A, B, C); AREA µm² (D,E,F,G)

From the data the mean area or mean length of charcoal particles from each site or collection may be calculated. These are tabulated in Table 3.3, which also includes a single sample (Bushrangers Catchment Rotorod collection, Chapter 5.5) not plotted on Figure 3.5. For comparison, area estimates have been converted to approximate length by assuming the mean length of charcoal particles was the square root of their mean area. Similarly, mean length has been converted to mean area by squaring. The mean size of charcoal particles is similar in samples from all sites or collections where the same size range has been used for analysis.

Table 3.3. Mean area and mean length of charcoal particles in all samples from each of eight sites or collections (see text for details), with the size range used for analyses and the total number of charcoal particles included in each estimate. Areas in brackets are squares of mean lengths where length size-classes were used; lengths in brackets are square roots of mean areas where area size-classes were used. The area range used for sites D-F is equivalent to about 15-120µm on a length range. Labels A to G correspond with those used for sites in Figure 3.5.

	Site	Charcoal Particles			
		Size range	Mean area μm^2	Mean length µm	Total number
A	Eden	6.5-104µm	(237)	15.4	1,256
B	Black Mtn	"	(424)	20.6	17,071
H	Bushrangers	"	(467)	21.6	107
C	Lashmar's	22-104µm	(1002)	31.7	944
D	Everitt	225-ca.14400μm^2	593	(24.4)	22,432
E	Curry	"	753	(27.4)	1,294
F	Collins	"	834	(28.9)	1,110
G	Duck	"	1019	(31.9)	1,307

The relationship between numbers of charcoal particles and their area or length is such that it is immaterial whether total number, total area or total length is used for estimating relative amounts of charcoal. One reason for the excellent correlations is that total area or total length has been calculated as the product of number with these parameters. This does not affect the conclusions as this is how, in practice, total area or length is determined, unless the point count method is used. If the differences evident in mean size of particles (Table 3.3) and in size distributions (Figure 3.5) are significant and useful for interpretation, then it would be worthwhile spending the extra time required for measuring areas or lengths of individual particles. This question will be discussed in Chapter 8.2.

Conclusion

The point count method of estimating area on slides of pollen preparations is so simple and rapid that analysis of charcoal can become a routine part of every pollen analysis, the fire history of sites being considered in the interpretation of their vegetation history. When techniques for preparing thin sections have improved, the method of estimating minimum volume should allow detailed reconstructions of fire history, with information about the frequency and relative intensity of fires and, if the sediment shows seasonal laminations, about the season of burn. These variables are the most important when considering the effects of fires on vegetation or on individual species over tens or thousands of years. In conjunction with time series analysis techniques, such as those described by Green (1981), more realistic interpretations may be made of the interactions of climate, fire and vegetation.

Chapter 4

CHARCOAL TRANSPORT: THEORY

The total amount of charcoal produced by a fire burning vegetation or plant debris is dependent on many variables, the most important of which are: the amount, type, arrangement, flammability and moisture content of fuel; local meteorological conditions, especially relative humidity and wind speed; the temperature at which the fuel burns; oxygen supply during combustion; and the area burned. Some charcoal is carried directly from a fire as particles in smoke but most remains on the ground or attached to standing vegetation and can be blown or washed away from a burned area long after the fire. Figure 4.1 summarizes the possible pathways of charcoal from production to preservation, for a longer or shorter term, or to destruction. Because charcoal is liable to physical, chemical or biological breakdown (Chapter 2), only a fraction of the charcoal produced is preserved in soils, sedimentary basins or the sea bed. Charcoal particles may follow a variety of simple or complex paths, with many cycles of suspension, movement and deposition, between their source and a preservation site.

Given a fossil assemblage of charcoal fragments in sediments, might it be possible to say where the fire was that produced it? Has most charcoal in sediments been carried there by wind or by water?

Airborne charcoal

The smallest particles in smoke may travel vast distances (Smith, *et al.*, 1973) and even the largest can be carried many kilometres; spot fires lit by burning bark have been recorded up to 30km ahead of

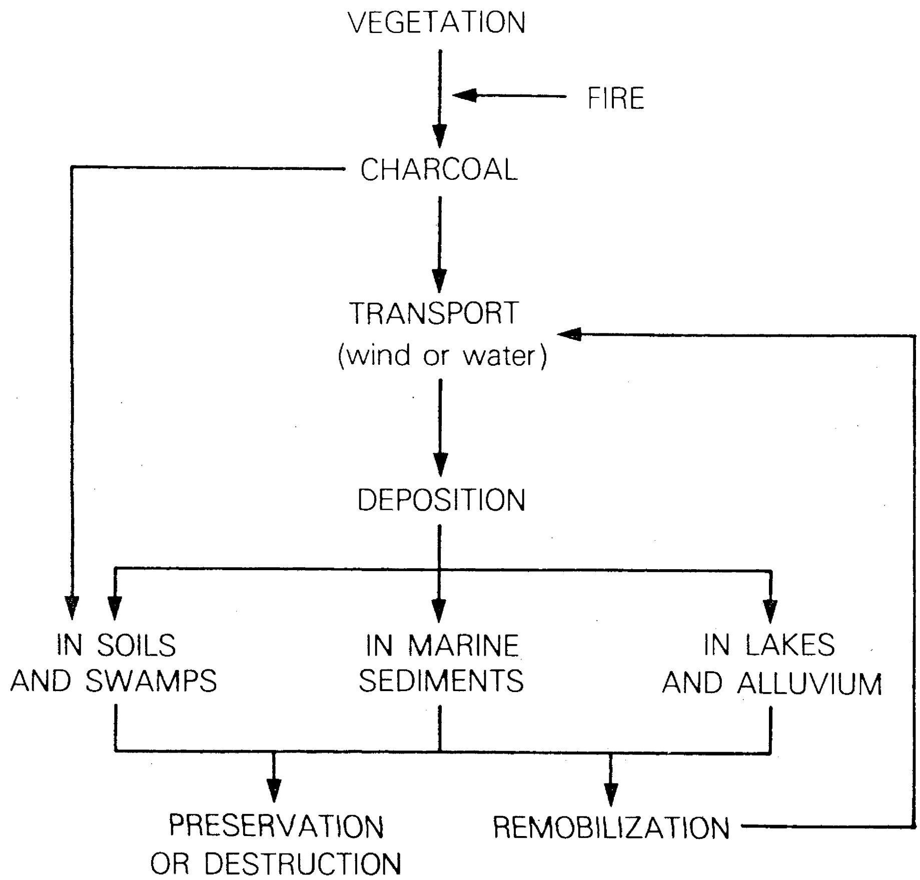


Figure 4.1. A summary of the possible pathways of charcoal particles from production to eventual preservation or destruction. Individual particles may go through many cycles of suspension and deposition by wind or water.

a large bushfire (Luke and McArthur, 1978, p.102). Smoke may be wind-driven close to the ground or lifted high in the atmosphere by convection. Smoke plumes vary greatly, depending on the amount and types of gases and particles produced, the intensity of the fire (which is a function of the amount of fuel, the rate of burning and the heat output of the fuel) and on meteorological conditions, particularly wind speed and atmospheric stability. Fires influence meteorological conditions, insignificantly with small fires, but on a large scale with intense fires. Convection above a fire increases wind speeds at ground level as air is drawn in, often in very large volumes (Vines, et al., 1971; Vines, 1977). Moisture in the entrained air of a convection column releases further heat when it reaches condensation level in the atmosphere. This may enable the convection column to break through a high level inversion layer, further stimulating convective activity. The movement of a smoke plume, and of the particles within it, is determined by convection, turbulence, gravity and wind direction and strength.

Many attempts have been made to model the behaviour of smoke plumes (Green and Lane, 1964; Pasquill, 1974; Turner, 1980). Most models have been devised to predict pollution from ground-level sources or smoke-stacks, but Pasquill's Gaussian model of smoke concentrations downwind (Pasquill, 1974) has been applied to prescribed burns of vegetation by Ross, et al. (1980). There are many difficulties with applying such models to bushfire smoke, the most important of which are: (a) a bushfire is a large area source shifting in time and space; (b) the concentration and composition of smoke vary in time and space; (c) convection and turbulence vary in time and space; (d) convection currents generated by a bushfire may be of vastly greater magnitude than those from an industrial or urban source so the vertical extent of the smoke plume may be much larger; (e) because a smoke plume over a bushfire may rise to a greater height than one from a smoke-stack, the smoke column may be subject to a greater range of wind speeds and directions, very different at ground level from those at a height of several thousand metres; and (f) turbulence and eddy diffusion within the smoke plume from a large bushfire may be very different from those in a plume from a small source.

Such models are inadequate for predicting quantities in smoke of charcoal particles of the size encountered in pollen analysis (>5μm diameter). Most smoke particles are less than 1μm diameter and may have a mean diameter of about 0.1μm (MacArthur, 1966; Vines, et al., 1971; Biswell, 1973; Schaefer, 1974; United States Department of Agriculture Forest Service, 1976). If the particle size frequency distribution were normal or, as is more likely, lognormal (skewed to the right) with a mean less than 1μm diameter, particles greater than 5μm diameter would fall in the tail of the distribution and their numbers would be very small relative to those of particles less than 1μm diameter. Even in the densest smoke, the concentration of larger charcoal particles is very low (Vines, et al., 1971).

Some attempts to measure and model downwind and crosswind distributions of larger particles released above the ground are reviewed by Green and Lane (1964, pp.296-300) and Pasquill (1974, pp.252-257). Many studies have been made of the airborne transport of pollen and spores. A few were aimed at improving interpretation of fossil pollen assemblages (e.g., Tauber, 1965, 1967; Janssen, 1966, 1973; Ritchie and Lichti-Federovich, 1967), but most have been concerned with pollination and the spread of fungal diseases in crops or with the transport of allergens (*e.g.*, Gregory, 1973; Edmonds, 1979; Close, *et al.*, 1978).

For larger particles with terminal velocities equal to or greater than vertical eddy velocities in the air, gravitation is the predominant deposition mechanism (Pasquill, 1974, p.252). Particles falling from a height (h) in a homogeneous medium would reach the ground at a distance (d) from their source determined by the terminal velocity (v_s) of the particles in that medium and the wind speed (u):

$$d = uh/v_s.$$

This basic model implies that particles with greater terminal velocities fall out closer to the source. Such size sorting with distance has been reported for dust (*e.g.*, Sarnthein and Koopmann, 1980; Schütz, 1979) and for tephra (*e.g.*, G.P.L. Walker, 1971). A further implication of the model is that particles of any given terminal velocity falling at one place might have come from a great height at a long distance or from a lesser height at a shorter distance. Add to this the dispersion of particles over time in the atmosphere, in both downwind and crosswind directions, the movement of the source of particles, changing meteorological conditions and different densities, shapes and, therefore, terminal velocities of charcoal particles, and it appears impossible to predict, other than in the most general terms, the distribution of airborne charcoal particles around a fire. Even if a model were devised that adequately described this distribution, it would be of no use in locating the source of a fossil charcoal assemblage, as many combinations of distance and direction from the source, meteorological conditions, fire intensity and area burned could result in similar collections of charcoal particles at the same deposition site.

Vines, et al. (1971) calculated that about 1.5-2.0% of fuel burned in their experimental fires was carried away as particles in smoke, of which approximately 55% were tar, 25% soot and 20% ash, although these proportions varied considerably. Charcoal particles were included as soot and, as mentioned above, larger particles were extremely rare. Although large charcoal particles can travel great distances, their comparatively small numbers and dilution in the air, dilution that increases with distance from a fire, make it unlikely that long-distance airborne transport produces significant concentrations of charcoal in sediments unless the sediment accumulation rate is very low.

Waterborne charcoal

If airborne transport of charcoal particles is difficult to model, then waterborne transport is even more so. Charcoal particles may fall directly into streams or lakes or be washed in by rainfall. They will be eroded, transported and deposited in the same way as all other constituents of sediment, forming part of the suspended and bed loads of streams and settling out according to terminal velocity and the speed and turbulence of flowing water (Leopold, Wolman and Miller, 1964; Gregory and Walling, 1973). Modelling of sediment transport has been reviewed in Graf (1971) and Vanoni (1975), while Peck (1974), Bonny (1978), Starling and Crowder (1981) and Solomon, et al. (1982) have investigated aspects of pollen transport in water.

The amount of charcoal washed from a burned area depends on a complex of catchment characteristics and antecedent moisture conditions, as well as the duration and intensity of individual rainfall events. Charcoal washed from the surface of the soil by overland flow, which might only occur on areas adjacent to stream courses, may be carried downstream and deposited and resuspended many times before reaching a more permanent deposition site. This might be an area of dense aquatic vegetation acting as a sediment trap or, more often, a place where the stream is slowed sufficiently for particles to fall out. As with airborne particles, those in water will be sorted according to terminal velocities, with larger particles settling out at stream velocities and turbulence sufficient to maintain smaller particles in suspension. Blong and Gillespie (1978) found the age of fossil charcoal in one alluvial sample varied by several hundred years depending on the size of the particles: the largest were oldest, implying that they had taken longer to travel downstream than smaller particles.

The yield of charcoal from wood burned at a range of temperatures was studied by Conaghan (1940; cited by Humphreys and Ironside, 1980). Fourteen _Eucalyptus_ and one _Melaleuca_ species were used and the mean yield of charcoal ranged from 28.5% at 950°C to 47.4% at 350°C. If 25-50% of fuel burned remains as charcoal, then much greater amounts of charcoal are left in a burned area than are widely dispersed in smoke. It is likely that most charcoal found in sediments has been carried there by water from the large store of charcoal left in catchments after fires. This is supported by K. Tolonen (in press) who, after reviewing Northern Hemisphere studies of fossil charcoal, concluded that only _in situ_ fires leave detectable carbon horizons in peat and that charcoal in lake sediments must be used if fire histories of larger regions are to be reconstructed. Corlett (1979) studied charcoal in mire sites in New Guinea and found evidence that charcoal was poorly dispersed, with the highest concentrations coming from vegetation no further than 2-3m away.

Conclusion

If most charcoal in sediments has been carried there by water, the amount deposited will depend as much on rainfall, soil moisture conditions and stream morphology as on the amount of charcoal produced. Further, if rainfall is insufficient to wash charcoal particles from a burned area after a fire, then that fire may not be represented in the sedimentary record. The charcoal catchment of a lake is unlikely to be the same as its pollen catchment, but the charcoal catchment can be more clearly defined.

It does not seem fruitful, even if it were possible, to model transport of charcoal to deduce where a fossil assemblage originated. Whatever the means of transport, the further a deposition site is from a source of charcoal, the fewer and smaller will be the charcoal particles deposited at that site.

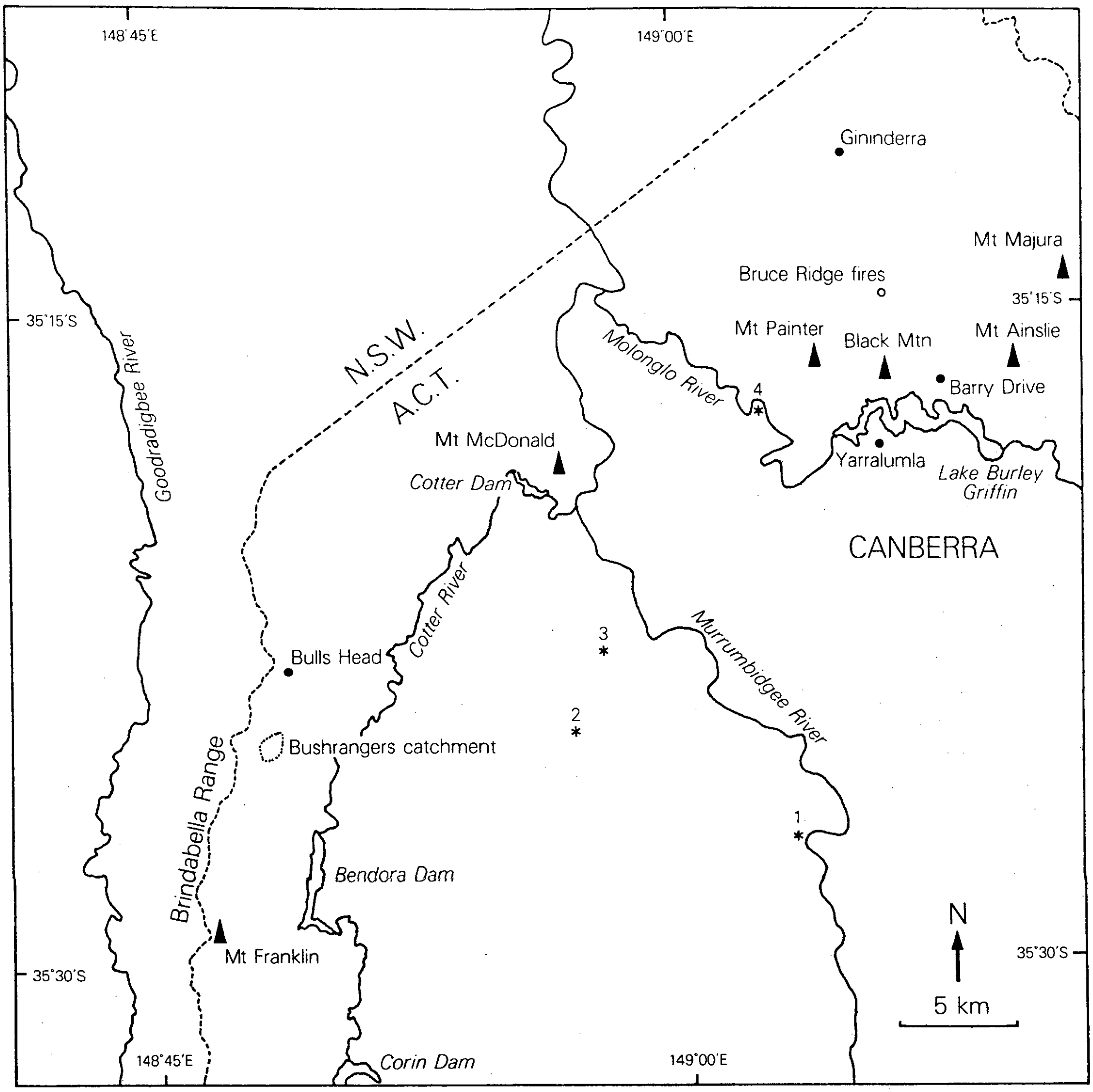
The conclusions drawn in this chapter from theoretical consideration of charcoal transport will be tested in Chapter 5, which describes experiments designed to estimate the amounts of charcoal produced by present-day fires and carried from fire areas by wind or water.

Chapter 5

CHARCOAL FROM PRESENT-DAY FIRES

The general conclusions drawn in Chapter 4 from consideration of the pathways by which charcoal moves from source to sink can be tested by measuring the amount of charcoal produced by and transported from present-day bushfires. For the purpose of interpreting the sedimentary charcoal record, the most important question is the relative significance of wind and water transport of charcoal. The catchment area of a deposition site for airborne charcoal is different from that for waterborne charcoal, and the pattern and timing of charcoal input to sediments also depend on the means of transport. In this chapter, experiments are described in which charcoal was collected around present-day fires. In Sections 5.1-5.5, particular fires are described, the methods used are given and the results presented. In the last Section (5.6), results from all collections are collated and general conclusions drawn. In Chapter 8, the results are compared with those from fossil samples.

Because it was not possible to set up the ideal experiment with fully monitored fires in selected locations, it was necessary to rely on experimental fires used by the CSIRO Division of Forest Research for other purposes and on chance wildfires. Charcoal was collected from two experimental fires (Sections 5.2 and 5.5) and two wildfires (Sections 5.3 and 5.4). In addition, pollen traps were used to collect charcoal that had been transported long distances (Section 5.1).



• Pollen traps

∗ Rotorod sites, Bushrangers fire

<u>Figure 5.1</u>. Map showing sites mentioned in Chapter 5.

5.1 Pollen traps, 1978-1981

In early 1978, Tauber type pollen traps (Tauber, 1974) were set up in meteorological enclosures at Bulls Head in the Brindabella Range west of Canberra and at Ginninderra, Yarralumla and Barry Drive (Canberra City) within the Canberra area (Figure 5.1). The contents of the three traps in Canberra were collected annually and those from Bulls Head at more frequent intervals. After traps were emptied, they were replenished with about 200ml of a solution of 20% glycerol, 40% formalin and 40% water. For the first year a solution of 10% glycerol, 5% formalin and 85% water was used, but this did not inhibit the growth of fungi.

The basic processing method was to filter the samples through a 250μm brass sieve, retaining the larger fraction, then collecting smaller particles from the filtrate on 5μm cellulose nitrate membrane filters (Chapter 2). Using a x10 objective on a microscope, the total area of charcoal on each filter was estimated by the point count method (Chapter 3.1), sufficient points being counted in each sample to give a relative standard deviation (s_p/P) of about 10%. Pieces of charcoal in the fractions collected on the 250μm sieve were separated under a binocular dissecting microscope and their size estimated using graph paper divided in square millimetres or a micrometer slide of 1mm in 0.01mm divisions.

The processing of each sample is summarized in Table 5.1 and details of departures from the basic procedure are as follows:

(1) The mass of fungal hyphae in some of the first year's samples, due to too little formalin in the solution in the traps, prevented direct filtration. These samples were centrifuged for 5 minutes at 4000rpm, passed through the potassium hydroxide and acetolysis steps

Table 5.1. Treatment of pollen trap samples; for details see text. Steps are arranged in sequence from left to right.

SAMPLES	PROCESSING									
	Potassium Hydroxide	Acetolysis	250µm Sieve	5µm Filter	Acetone	Ethanol	T-Butyl Alcohol	Silicone Oil	Xylene	5µm Filter
(a) < 250µm FRACTION:										
Bulls Head										
16.3.78-14.7.78			x	x	x	x	x	x	x	x
14.7.78-5.11.78			x	x	x	x	x	x	x	x
5.11.78-18.1.79			x	x						
18.1.79-26.5.79			x	x	x	x	x	x	x	x
26.5.79-26.9.79			x	x	x	x	x	x	x	x
26.9.79-29.2.80			x	x	x	x	x	x	x	x
29.2.80-30.7.80			x	x						
30.7.80-18.1.81			x	x						
18.1.81-22.6.81			x	x						
Barry Drive										
3.1.78-7.3.79	x	x	x			x	x	x	x	x
7.3.79-19.3.80			x	x	x	x	x	x	x	x
19.3.80-19.1.81			x	x						
Gininderra										
9.2.78-5.2.79	x	x	x			x	x	x	x	x
5.2.79-19.3.80			x	x	x	x	x	x	x	x
19.3.80-19.1.81			x	x						
Yarralumla										
9.2.78-5.2.79	x	x	x			x	x	x	x	x
5.2.79-19.3.80			x	x	x	x	x	x	x	x
19.3.80-19.1.81			x	x						
(b) > 250 µm FRACTION:										
Bulls Head										
16.3.78-14.7.78										
14.7.78-5.11.78										
5.11.78-18.1.79		x	x	x						
18.1.79-26.5.79	x	x	x			x	x	x	x	x
26.5.79-26.9.79										
26.9.79-29.2.80										
29.2.80-30.7.80		x	x	x						
30.7.80-18.1.81		x	x	x						
18.1.81-22.6.81		x	x	x						
Barry Drive										
3.1.78-7.3.79										
7.3.79-19.3.80		x	x	x						
19.3.80-19.1.81		x	x	x						
Gininderra										
9.2.78-5.2.79										
5.2.79-19.3.80		x	x	x						
19.3.80-19.1.81		x	x	x						
Yarralumla										
9.2.78-5.2.79										
5.2.79-19.3.80		x	x	x						
19.3.80-19.1.81		x	x	x						

of the pollen preparation procedure (Chapter 2), then filtered through a 250μm sieve, both fractions being retained. The smaller size fraction was taken through two changes of absolute ethanol and two of tertiary butyl alcohol into silicone oil. Any charcoal in the larger size fraction was measured directly.

(2) Prior to the realization of the advantages of observing particles on cleared membrane filters (Chapter 2), the filters were removed by dissolving them in several changes of acetone, with centrifuging between, then passing the samples through two changes each of absolute ethanol and tertiary butyl alcohol to silicone oil. To re-collect these samples on filters, the silicone oil containing the samples was dissolved in xylene, filtered, and the filters air dried and mounted on slides.

(3) Some of the sample fractions collected on the 250μm sieve contained so much material, particularly insect remains, that it was difficult to separate charcoal particles manually. These samples were then acetolysed and passed again through a 250μm sieve before being collected on filters, dried and mounted. Any charcoal retained on the 250μm sieve was measured.

As processing affects the amount of charcoal (Chapter 2), only those samples collected and examined on the filters without chemical treatment give an accurate estimate of the input of carbonized particles to the traps. Correction factors derived from the experiment described in Chapter 2 may be applied to improve the estimate for treated samples: the original area of charcoal in that experiment was 1.3 times the area after acetolysis and 1.4 times the area after potassium hydroxide and acetolysis.

This experiment was designed only to estimate roughly the amount of charcoal which might be deposited on a surface from long-distance airborne transport of particles in normal years and, it was hoped, at times of extensive local bushfires. No attempt was made, therefore, to empty all the traps on one day or on the same date each year. The traps are not equivalent to a lake or swamp surface in their collecting capacity, possibly collecting more particles than an equivalent surface area of water and less than that of a swamp, depending on surface and vegetation roughness. Results of wind tunnel tests of trap efficiency (Tauber, 1974) are not useful; what is needed are the relative efficiencies of the traps and various kinds of natural collecting surfaces.

Results are presented graphically in Figure 5.2 as average daily inputs of carbonized particles over each period sampled with, for Bulls Head, the average input over times comparable with the Canberra samples. Amounts after correction for processing losses are included; in few cases are these significantly different from the uncorrected areas. Input to the Barry Drive trap was much higher than to any other; most of the carbonized particles appear to be soots, probably from exhaust fumes and surrounding urban areas. Some of this carbon also occurs in the Yarralumla samples, but there is none in those from Ginninderra and Bulls Head, both of which are outside the Canberra urban area. Some of the wood charcoal in the Canberra traps is likely to be from domestic sources.

During the three-year collection period, smoke haze covered Canberra many times from fires in the Blue Mountains, west of Sydney, on the far south coast of New South Wales, in eastern Victoria and in the Brindabella Ranges and Snowy Mountains, west and south-west of

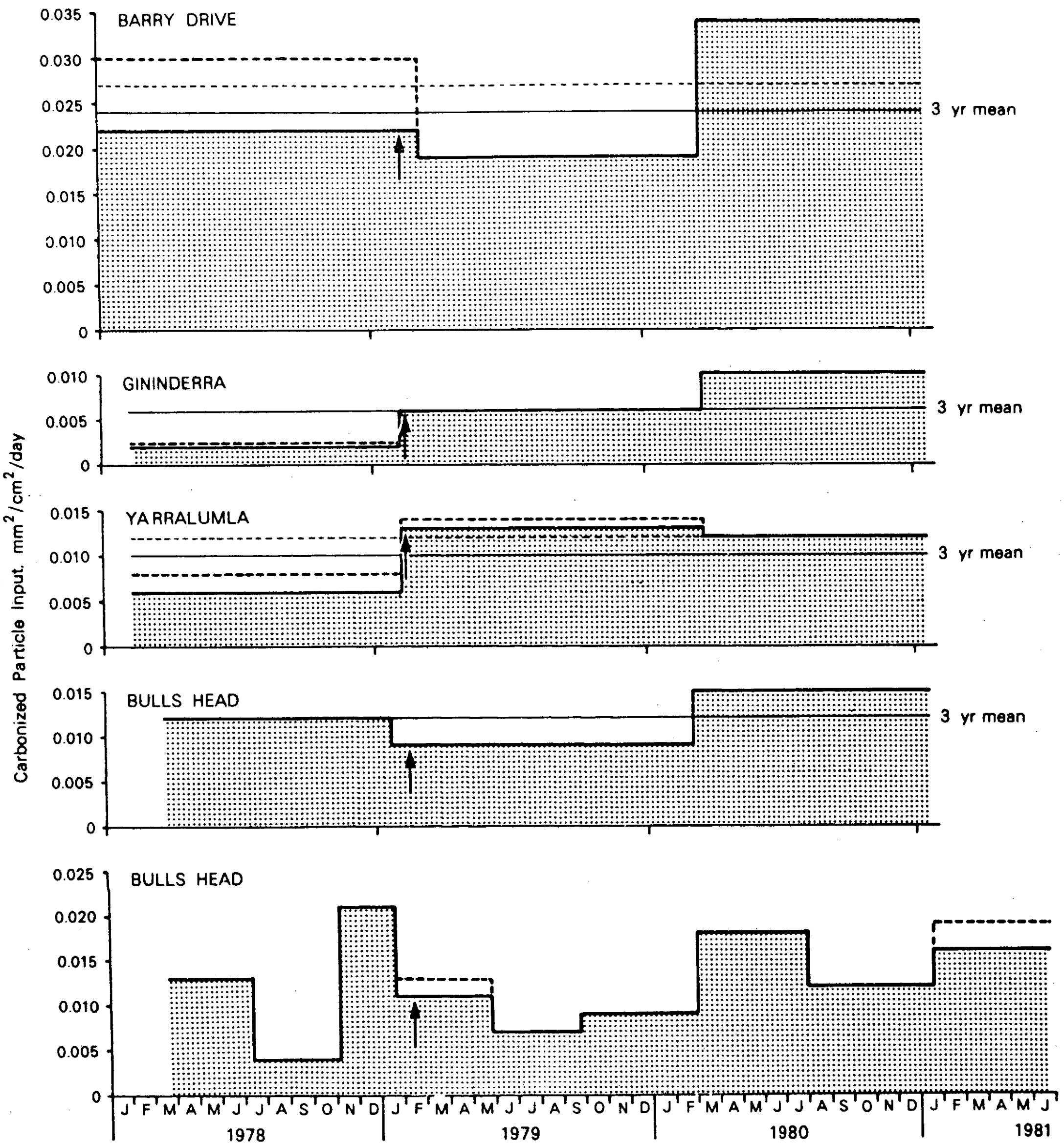


Figure 5.2. Mean daily input of carbonized particles to pollen traps over each collection period (shaded) with, for Bulls Head, input over periods equivalent to the other traps. Mean daily input over three years is also indicated. Dashed lines are amounts corrected for likely losses in processing. Acetolysed samples have been multiplied by 1.3, those both acetolysed and treated with potassium hydroxide by 1.4. Arrows indicate 13 February, 1979, a day of extensive bushfires in the Canberra region.

Canberra. Every summer there are small grass fires within the Canberra urban area and on 3 February, 1979, there was a forest fire on Mt Majura (Figure 5.1). On 13 February, 1979, there were many large bushfires close to Canberra and one on Mt Painter, near the centre of Canberra (Figure 5.1). Smoke from this fire blew directly over the Barry Drive pollen trap, only 3-5km distant. The amount of charcoal collected by the traps in the period covering 13 February, 1979, is not significantly different from that collected in years with no large fires close to Canberra, but the more detailed Bulls Head record does show increased input of charcoal at times when fuel reduction burning was carried out nearby.

Over the collection period, the mean annual input of carbonized particles to the four pollen traps was:

(1) Barry Drive, 3.1.78-19.1.81 : 8.7mm^2/cm^2/y
(corrected for processing losses: 10.0mm^2/cm^2/y)

(2) Ginninderra, 9.2.78-19.1.81 : 2.1mm^2/cm^2/y
(corrected : 2.2mm^2/cm^2/y)

(3) Yarralumla, 9.2.78-19.1.81 : 3.8mm^2/cm^2/y
(corrected : 4.2mm^2/cm^2/y)

(4) Bulls Head, 16.3.78-18.1.81 : 4.2mm^2/cm^2/y
(corrected : 4.3mm^2/cm^2/y)

It is evident that there is a general background of charcoal and carbon particles larger than about 5μm diameter which are transported long distances in the atmosphere directly from their source or resuspended and moved by wind. Local fires may or may not significantly increase the amount of charcoal falling on a surface; this depends on the location of the collecting surface relative to the fire and on meteorological conditions at the time of the fire.

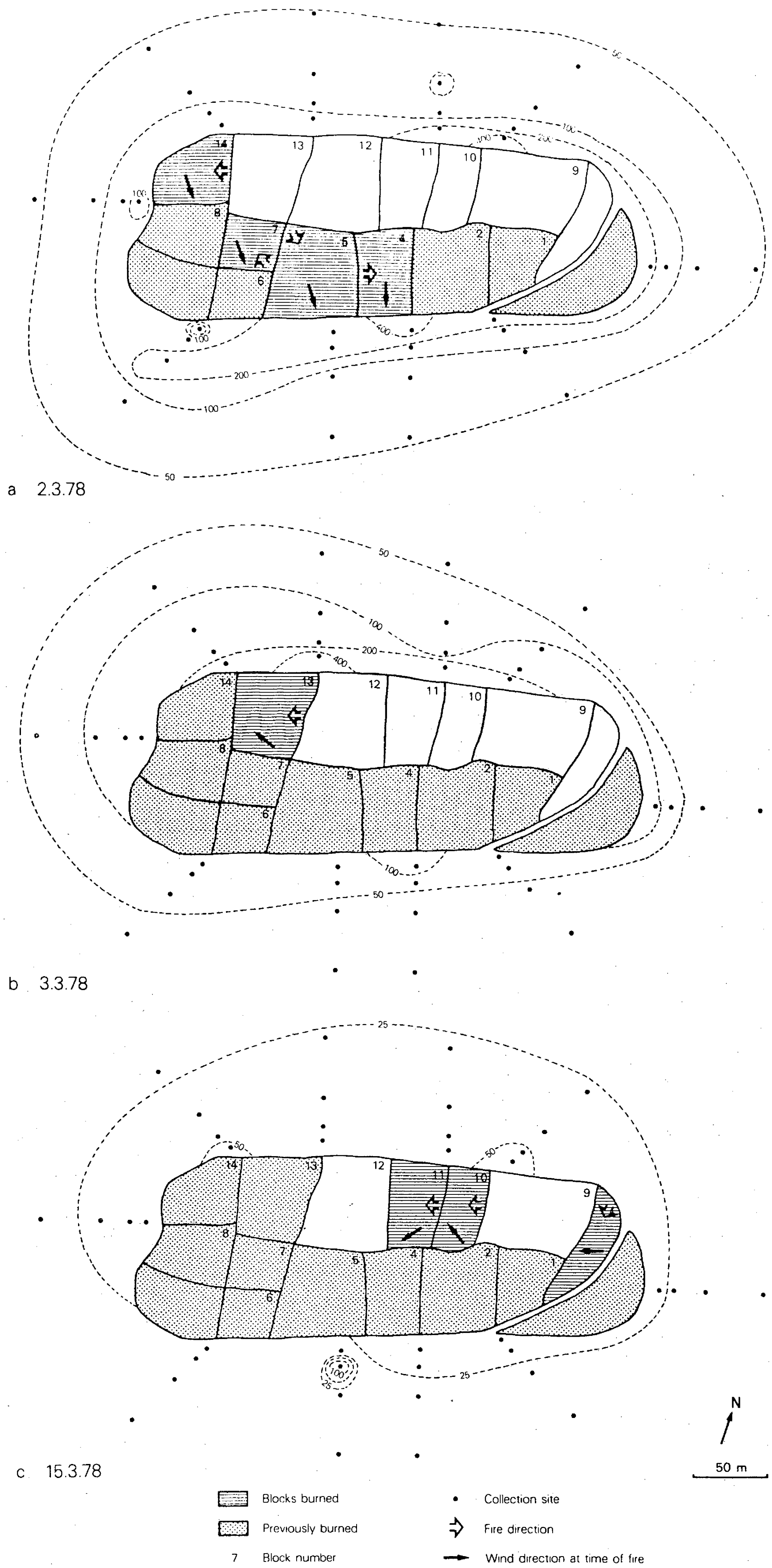
5.2 Black Mountain, 1978

In February and March, 1978, a series of small experimental fires was lit on Bruce Ridge, to the north of Black Mountain near the centre of Canberra, A.C.T. (Figure 5.1). This area of Eucalyptus rossii and E.macrorhyncha woodland (Frontispiece) had originally been reserved for the production of firewood, and many trees were coppiced in the early 1940's. In 1978, the sparse understorey was predominantly Acacia genistifolia, Daviesia mimosoides, Dillwynia retorta and Exocarpos cupressiformis, with an intermittent ground cover of several shrubs, grasses and species of Liliaceae. The area was similar to that described by Purdie and Slatyer (1976). The weight of fine fuel (<6mm minimum dimension) in the litter was about 15t/ha (N.P. Cheney, pers. comm.).

On five days between 27 February and 15 March, 1978, ten blocks within the experimental area were burned (Figure 5.3). Each fire was planned to be predominantly one of three kinds: (a) a head fire, with the wind blowing from the burned to the unburned area (Blocks 5, 11 and 13); (b) a flank fire, with the wind at right angles to the fire front (Blocks 2, 4, 10 and 14); and (c) a back fire, with the wind blowing from the unburned to the burned area (Blocks 1, 7 and 8). Depending on the variability of meteorological conditions in time and space, any one fire may be, and some of these fires were, a combination of these types. In addition to the numbered blocks, some areas were burned as fire breaks (previously burned blocks, Figure 5.3).

On three days that blocks were burned, microscope slides coated with a thin layer of petroleum jelly were laid out on the ground along ten transects defined by compass direction. Four slides were placed

Figure 5.3. Maps showing experimental fires on Black Mountain on three days in March, 1978, when airborne charcoal particles were collected. Lines have been drawn connecting areas of equal concentrations of charcoal particles for each of the three days.



a 2.3.78
b 3.3.78
c 15.3.78
N
50 m
Blocks burned
Previously burned
7 Block number
Collection site
Fire direction
Wind direction at time of fire

along each transect at 10m, 20m, 40m and 80m from the edge of the experimental area (Figure 5.3). Slides were put out before burning began on 2 March, changed at the same time on 3 March and the second set collected next morning. On 15 March slides were put out in the morning and collected in the evening. Using a x10 objective on a microscope, all charcoal particles of maximum dimension greater than 6.5µm were counted on several transects of each slide and, from the area traversed in counting, the total number of particles per square centimetre of surface was calculated. Particles were counted in size classes according to their maximum dimension using the divisions of a standard eyepiece micrometer scale (Figure 3.1). At the magnification used, each division was 6.5µm. Where the end of a particle fell on a division line, the particle was included in the division above. Particles of length between 104µm and 930µm (the diameter of the field of view) were lumped in one class, those larger in another, and aggregates of many particles tallied separately. Particles shorter than one division were not included as their identification was uncertain and the lower limit of the class would have been not zero, but the level of resolution of the microscope.

Results are presented in Figure 5.3 by lines joining equal concentrations (number/cm^2) of charcoal particles on each of the three sampling days. Blocks burned on each day are indicated, as are previously burned areas, the direction of each fire and the wind direction at the time of each fire.

The concentration (number/cm^2) of charcoal particles decreased with distance from the burned areas, while the distribution of charcoal reflected, to some extent, wind direction at the time of the fires. This is particularly evident on the day when only one fire was lit (Figure 5.3b). Neither the area burned each day nor the type of fire is reflected in numbers of charcoal particles.

Listed in Table 5.2 are correlation coefficients for regressions between logarithms of numbers of charcoal particles and logarithms of distances from the nearest fire, from the nearest burned area (burned that day or preceding days) and along the transects, for each of the three collection days. The best correlations were found on the day when only one fire was lit (3.3.78), suggesting that results from the other days were complicated by changing wind directions between fires. When the sum of the three daily collections was compared with distances, the best correlation was with distance along transects (Figure 5.4). The slope of this regression line (-0.58), and of all others where there was a significant correlation between number and distance (-0.47 to -0.58), indicates that the number of particles decreased with approximately the inverse square root of the distance (slope = -0.50).

Table 5.2 Correlation coefficients (Pearson's r) for regressions between logarithms of numbers of charcoal particles per square centimetre and of distances from the experimental area for the three sampling days.

Day	Distance		
	From nearest fire	From nearest burned area	Along transects
2.3.78	-0.2911	-0.3612	-0.5284
3.3.78	-0.6658	-0.3851	-0.6739
15.3.78	-0.2936	-0.3776	-0.4780

The reduction in numbers of charcoal particles with distance from the fires may also be represented by the diagram in Figure 5.5. The total input per square centimetre over three days (y-axis) is plotted against distance from the experimental area (z-axis) and size class (x-axis). It is evident that while numbers decrease with distance,

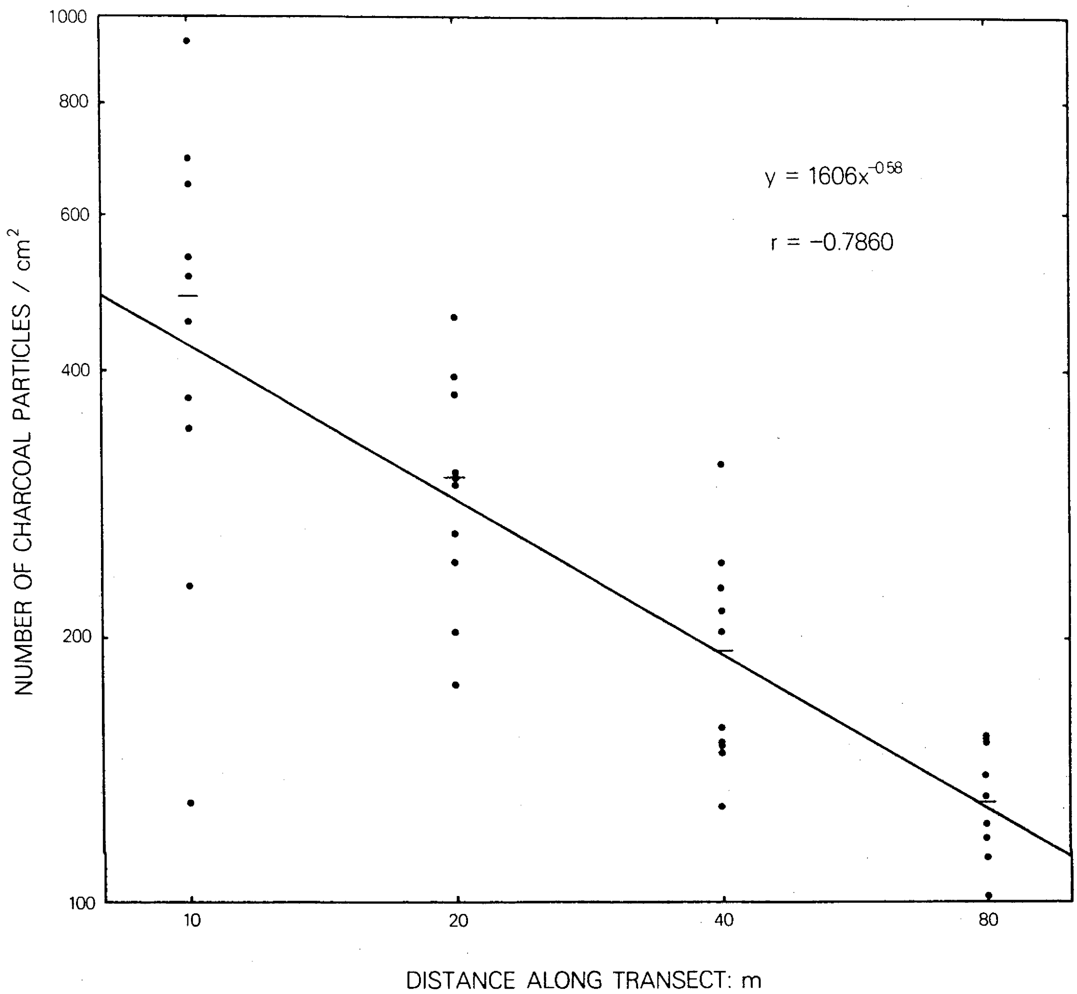


Figure 5.4. The correlation between numbers of charcoal particles per square centimetre and distance along transects from the experimental area, plotted on logarithmic scales.

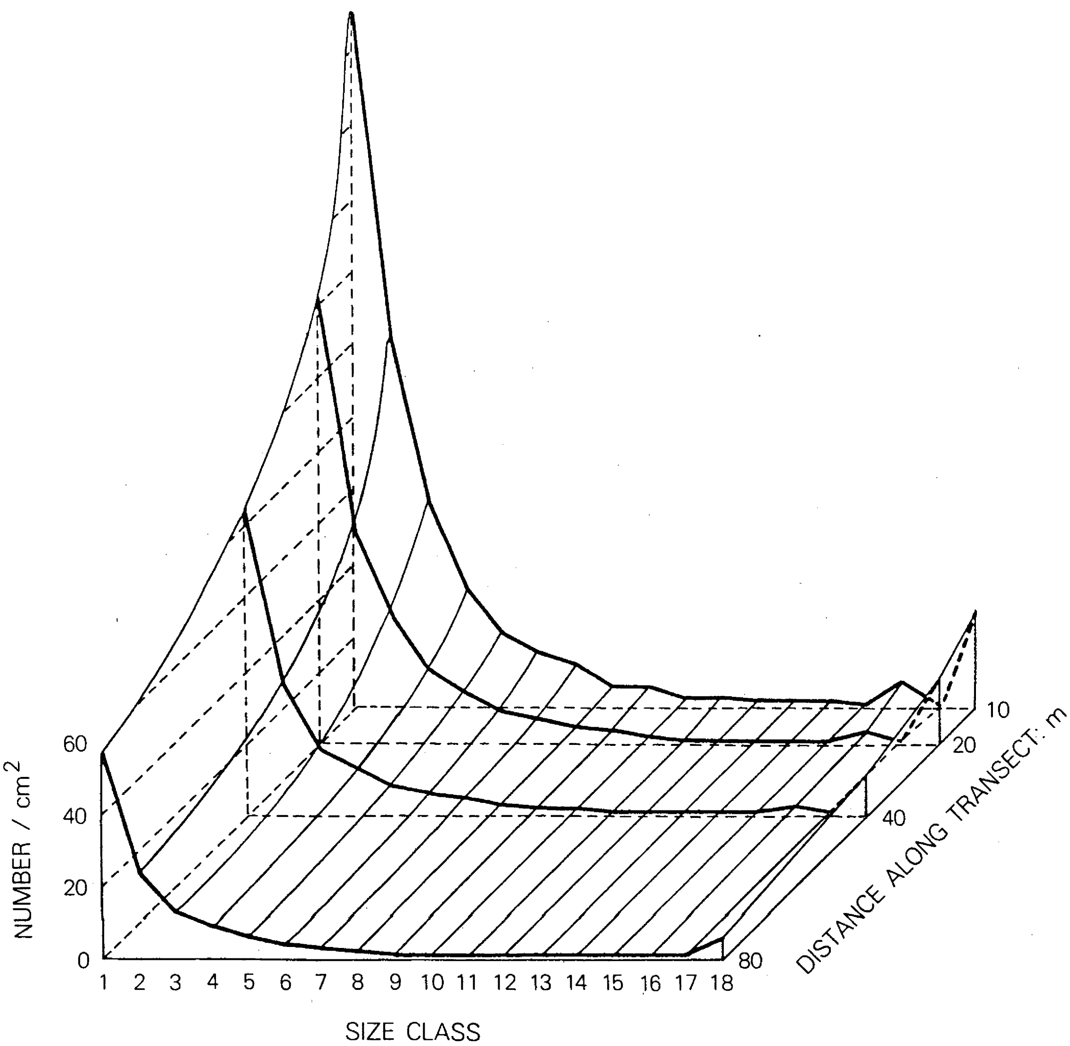


Figure 5.5. Changes in numbers of charcoal particles per square centimetre (y-axis) with distance along transects (z-axis) and size of particles (x-axis). Length size classes 1 to 15 are equally spaced at 6.5μm intervals from an arithmetic mean of 9.75μm in class 1 to a mean of 100.75μm in class 15; class 16 contains particles between 104μm and 930μm; class 17, those longer than 930μm; and class 18, aggregates of many particles.

the four curves of size distribution remain of the same form. The reduction in numbers is not due to larger particles falling out closer to the experimental area, but to fewer particles of all sizes travelling greater distances.

These results confirm the conclusion drawn in Chapter 4, that a simple model of charcoal particles being lifted by convection currents in smoke above a fire, carried away by wind and brought back to earth by gravity at predictable distances is inadequate. The spread of charcoal around the experimental area was affected by turbulence, changes in wind direction and strength, the type and intensity of fires, the amount and moisture content of fuel, the amount of smoke and the height of the convection column, the area burned, the length of time each fire lasted, filtering of particles by vegetation, disturbance by people and equipment within the experimental area and the distribution by wind of charcoal particles from burned areas after the fires were out. The last is suggested by the small number of particles collected on 15 March, when slides were exposed for the time of the fires only, compared with the numbers on the other two days, when slides were left overnight after the fires. On the other hand, there was little correlation between number of particles and distance from the nearest burned area (Table 5.2).

The area burned on the three sampling days totalled 1.68ha, so the amount of fuel consumed was about 25t. The mean concentration of airborne charcoal particles in the area and size range sampled was 282/cm^2.

5.3 Eden, 1979

A high intensity wildfire burned through 33km^2 of forest south-west of Eden, N.S.W., on 9th January, 1979. The area burned included several small catchments in the upper Wallagaraugh River (Figure 5.6) which had been equipped before 1978 for monitoring the effects on hydrology of clear-fell logging (Olive, *et al.*, 1978; Rieger, *et al.*, 1979; Burgess, *et al.*, 1980, 1981; Mackay and Cornish, 1982). Water samples were taken regularly either manually or automatically from 140° sharp-crested V-notch weirs which had been constructed at the outlet of each catchment.

The following brief description of the area is a summary of information in the above references and a fuller account of the vegetation may be found in Heyligers (1977). The catchments, on Silurian-Devonian granitoids, have steep slopes, mostly between 10° and 20°. The vegetation is dry sclerophyll forest (open forest and tall open forest), the dominant trees being *Eucalyptus sieberi*, *E.obliqua*, *E.muelleriana*, *E.cypellocarpa* and *E.consideriana*. The most common understorey species are *Acacia terminalis*, *Banksia serrata*, *Casuarina littoralis*, *Persoonia linearis* and *P.levis*, with a ground cover of grasses, chiefly *Poa* spp. and *Danthonia* spp., and sedges, particularly *Gahnia* spp. Some rainforest species occur in gullies, and swampy areas have a dense cover of *Melaleuca squarrosa* and *Leptospermum juniperinum*.

Estimates were made of the charcoal content of water samples collected between 1 September, 1978, and 14 January, 1980, from catchment 4 (area 88.3ha, Figure 5.6) which had not been logged before the fire. Suspended sediment was collected on cellulose nitrate membrane filters with a pore size of 5μm which were then mounted on

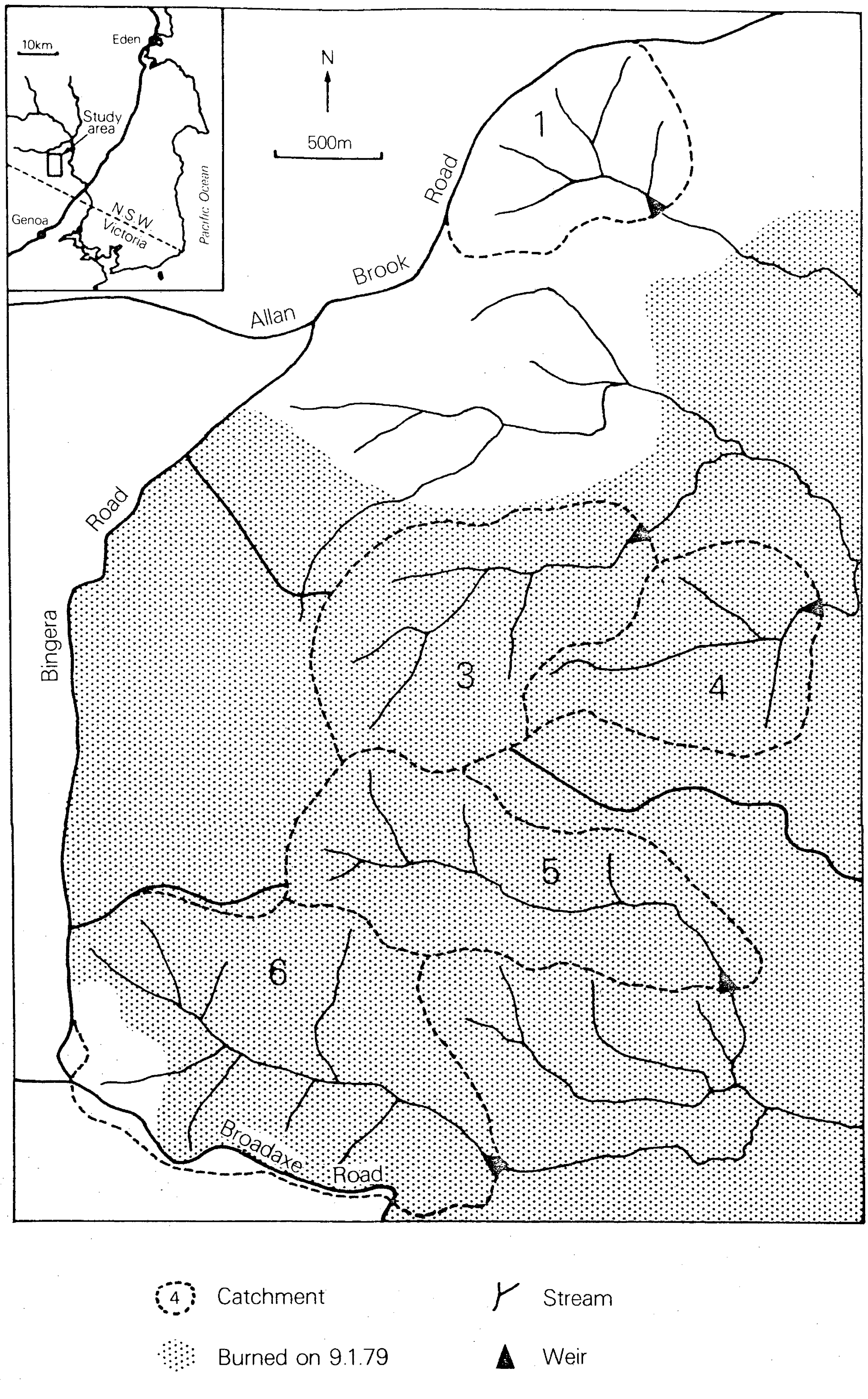


Figure 5.6. Map of the experimental catchments near Eden, N.S.W. The shaded area was burned on 9 January, 1979. Location is shown in the inset. Adapted from Burgess, et al., 1981, Figure 1.

microscope slides (Chapter 2). The area of charcoal on each filter was estimated by point counting (Chapter 3.1) using a x10 objective, counting continuing until 2200 points had been applied to each filter. Sample volumes were measured and ranged from 11ml to 94ml, with most 60-80ml. The estimated area of charcoal in a unit volume of water was then calculated.

A further set of water samples from catchment 5 (area 140.0ha, Figure 5.6), which had been partly clear-felled before the fire (Rieger, et al., 1979), was collected before and during the first substantial rainfall event after the fire, 14-17 March, 1979. These samples were centrifuged at 3000rpm for 1 minute, resuspended in 2ml water and mounted directly on microscope slides. Coverglasses were sealed with varnish to prevent evaporation. Charcoal particles were counted in size classes based on maximum dimension, measured by an eyepiece micrometer (Figure 3.1) with divisions of 6.5µm at the magnification used.

Measurements of discharge through the weirs at the times the samples were taken and of sediment concentrations of the samples were provided by J.S. Burgess (Geography Department, Royal Military College, Duntroon).

Results from catchment 4 (unlogged) are summarized in Table 5.3, which lists means of discharge, charcoal concentration and sediment concentration for samples collected before and after the fire. The entire sampling period was exceptionally dry and there was only one rainfall event of any magnitude. This occurred between 15 and 17 March, 1979, 65-67 days after the fire, with maximum rainfall of 80mm/day on 15 March (Burgess, et al., 1980). Total rainfall over the twelve months after the fire was only 578mm (J.S. Burgess, pers.comm.), compared with mean annual rainfall of 939mm at nearby Timbillica (Olive, et al., 1978). In this twelve month period, only five days had 20mm or more of rain. Because of the low rainfall, the data have been separated into samples collected at low discharge, usually weekly, and those collected at high discharge, through one pre-fire and one post-fire rainfall event, with four samples collected at high discharge between 288 and 370 days after the fire.

Table 5.3. Mean values of charcoal concentration (C), suspended sediment concentration (S) and discharge (Q) for water samples from catchment 4 before and after the fire of 9 January, 1979. The number of samples (n) used in each calculation is indicated. Samples taken at low (a) and high (b) discharge have been separated.

	C mm^2/l	S mg/l	Q l/sec	n
(a) Discharge <5 l/sec:				
Pre-fire	11	4	1.1	12
All post-fire	17	3	0.6	40
Post-fire till rainfall event	25	4	0.5	23
Post-fire after rainfall event	6	2	0.8	17
(b) Discharge >5 l/sec:				
Pre-fire rainfall event	71	24	52	8
Post-fire rainfall event	74	12	93	24
Later post-fire	12	7	26	4

There is little difference in mean charcoal concentration before and after the fire, whether at low discharge or during the two rainfall events. Samples taken at low discharge between the fire and the post-fire rainfall event have higher charcoal concentrations than equivalent samples taken before the fire or after this event. Charcoal concentration in the first sample taken when discharge rose on 15 March was exceptionally high: $295mm^2$/litre at a discharge rate of 17 litres/second. No samples were taken over the following 24 hours, when rainfall reached its maximum, but charcoal concentration was again high (up to 313mm^2/litre at a discharge of 121 litre/sec) during a subsequent peak in discharge on 16-17 March. In an adjacent catchment (number 3, Figure 5.6) exceptionally high sediment concentrations were recorded in the first few samples collected during the same rainfall event and during a minor rainfall event ten days earlier (Burgess, et al., 1980).

These results suggest that the only time significant amounts of charcoal were washed off the catchment was in the first post-fire rainfall events, with the highest concentrations at the beginning of those events. Burgess, et al. (1980) conclude from their studies of sediment yield in catchment 3 that rainfall in excess of 20mm/day might be necessary before post-fire increases in suspended sediment and solute load become detectable. This would also apply to the charcoal fraction of the suspended sediment.

Over all samples (n = 92) there was little correlation between charcoal and discharge (r = 0.4786) and slightly better correlations between sediment concentration and discharge (r = 0.5767) and between charcoal and sediment concentrations (r = 0.6333). In post-fire samples collected before and during the rainfall event, there was more charcoal per unit weight of sediment than in the pre-fire period (Table 5.3). This is illustrated in Figure 5.7 which shows the regressions between charcoal and sediment concentrations before and after the fire. After the large post-fire rainfall event both charcoal and sediment concentrations were low (Table 5.3) and not correlated. What little surface runoff there was during this dry period would have been over ground largely depleted of charcoal by the first post-fire rainfall. Subsequently, little charcoal might be washed from the catchment until the amount, duration and intensity of

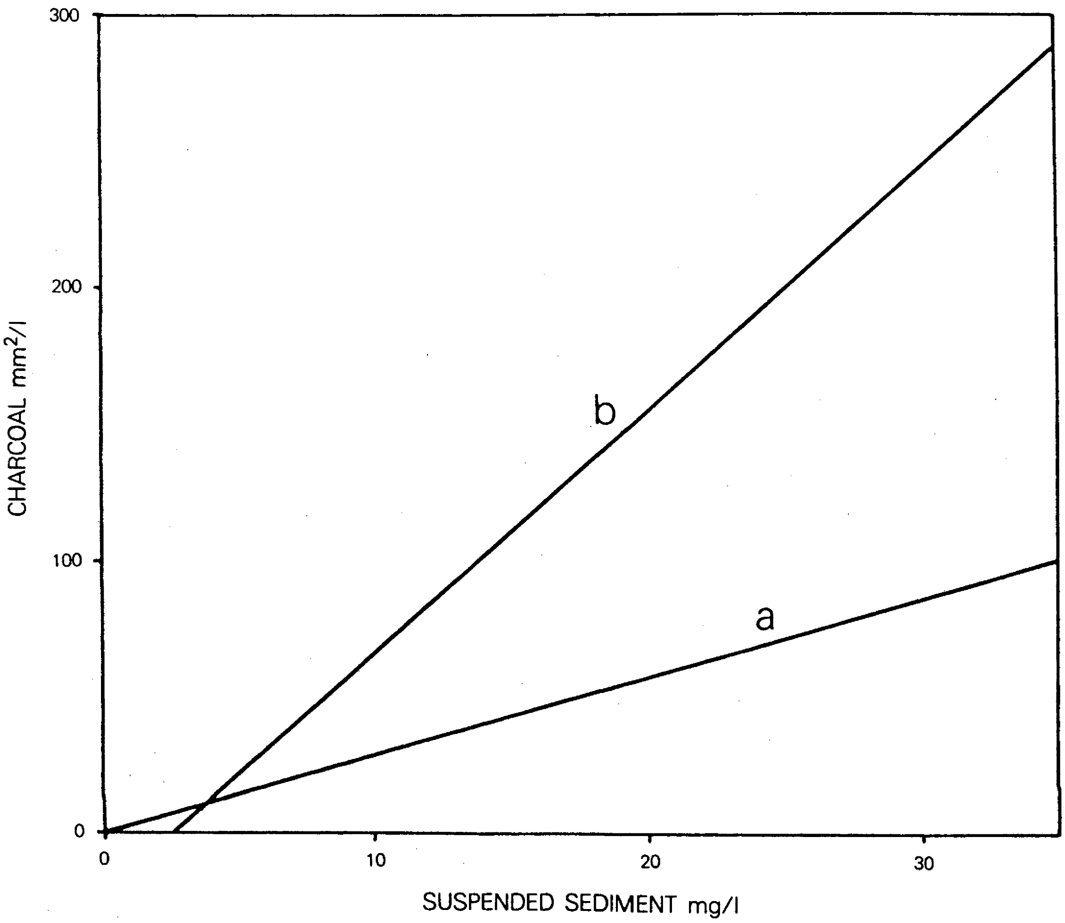


Figure 5.7. Regressions between charcoal and sediment concentrations of water samples from catchment 4 (see Figure 5.6): (a) all pre-fire samples ($n = 18$, $r = 0.7767$, slope = 2.92); (b) all post-fire samples up to and including the rainfall event of 15-17 March, 1979 ($n = 47$, $r = 0.7394$, slope = 8.89). There was no correlation ($r = 0.0143$) between charcoal and sediment concentrations in the 25 samples collected after 17 March, 1979.

rainfall were sufficient to create larger areas of overland flow. With continuing drought, this might take some years. In the meantime, regeneration of vegetation and the formation of a new litter layer would prevent much of the charcoal being washed away when substantial rain eventually fell.

The fourteen samples collected between 14 and 17 March, 1979, from catchment 5 showed an excellent correlation between charcoal concentration (number/litre) and sediment concentration ($r = 0.9149$), but little correlation between charcoal or sediment concentrations and discharge ($r = 0.5964$ and 0.4746 respectively). Charcoal concentrations ranged from 1.8×10^5 to 1.7×10^8 particles/litre, with a mean of 4.4×10^7/l; sediment concentrations ranged from 15 to 2520mg/l (mean 437mg/l); and discharge ranged from 7 to 605 litres/second (mean 296 l/sec). The size distribution of charcoal particles in these samples is discussed in Chapters 3.2 and 8.2.

The amount of charcoal washed from the burned catchments depended on the intensity of rainfall, and increased significantly at times of high discharge. The largest amounts of charcoal were removed in the first rainfall events, but charcoal was still being washed from the catchments a year after the fire.

5.4 Sutton and Wollondilly, 1979

On 13th February, 1979, a day of extreme fire weather, many fires started in the grasslands and forests of the Southern Tablelands region of New South Wales. Several of these fires burned out of control for about twelve hours; those in inaccessible country continued flaring up for several days. One fire began about 3 p.m. just south of Hall, A.C.T., and spread quickly, fanned by a strong westerly wind which changed about 5.10 p.m. to a south-westerly (Figure 5.8). The fire burned out about 170km^2 of pasture and woodland before being brought under control about 5 a.m. next day.

Rotorod samples

While this fire was burning, smoke particles were sampled with a rotating impaction sampler (Rotorod), with a thin coating of petroleum jelly on the collecting surfaces. These portable, battery-operated samplers, described in Ogden, et al (1974), collect particles on the leading edges of removable rods which are rotated through the air being sampled. Knowing the speed of rotation, the area of the collecting surface and the sampling time, the total volume of air sampled can be calculated. Sampling rods are mounted in a special holder under a microscope and, using incident light, the number or area of particles on the collecting surfaces is estimated and the concentration of particles in the air sampled is calculated. For this experiment, H-shaped collectors were used, the collecting surfaces being the leading edges of the two vertical parts of the rods. Two samples, one in a clockwise direction and one anticlockwise, could be taken with each collector. The collecting efficiency of the sampler is not known, although said to be high (Ogden, et al., 1974, p.56), but the narrow H-shaped collectors are designed for particles of diameters 1-10µm, rather than the larger particles of interest here. Collecting efficiency depends, in part, on the adhesive used. Solomon, et al. (1980) tested the relative efficiencies of four adhesives widely used on rotating impaction samplers. These four, including petroleum jelly, were recommended above others, and only silicone grease was found to be marginally more efficient than petroleum jelly. Because the collecting efficiency of the sampler is not known, results cannot be used as measures of absolute

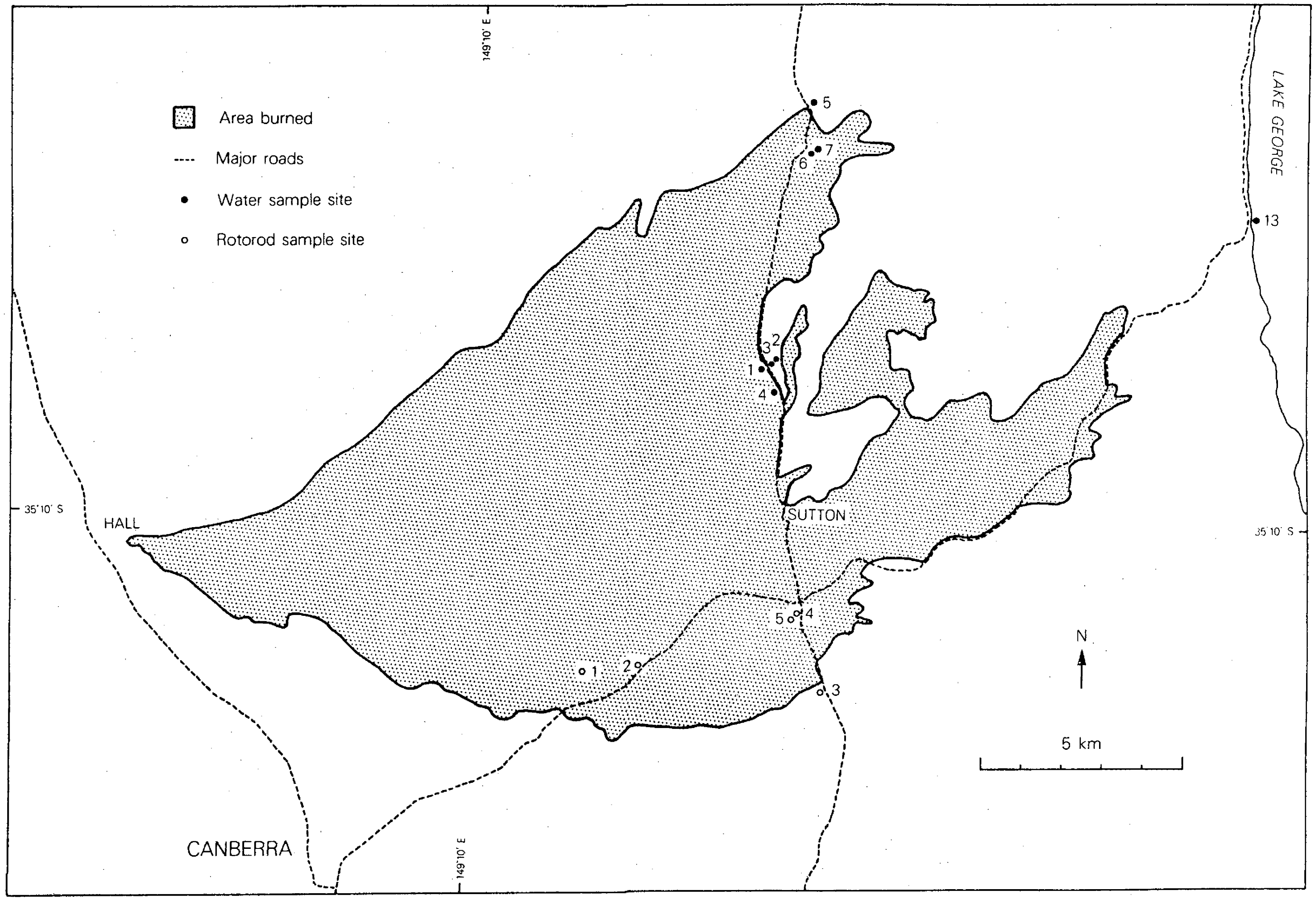


Figure 5.8. Map of the area burned in the Sutton fire on 13 February, 1979, showing locations of farm dams sampled and of Rotorod samples. From a fire map prepared by N.P. Cheney of the CSIRO Division of Forest Research.

concentrations of charcoal particles in smoke, but provide estimates which may be compared.

Five samples were taken with the Rotorod, at locations indicated in Figure 5.8, when the fire was burning through grassland with strong winds carrying the smoke ahead of the fire front. Samples 3, 4 and 5 were taken directly in front of the head of the fire and samples 1 and 2 on the flank of the fire head. Using a x10 objective on a microscope, the area of charcoal in each sample was estimated by point counting (Chapter 3.1), 1470 points being applied to each sample, half the number on each of the two collecting surfaces. The concentration of charcoal in area per unit volume of air was calculated and results are presented in Table 5.4.

The concentration of larger charcoal particles (>5μm length) was high immediately in front of the fire, but fell off rapidly with distance. When the densest smoke was overhead (sample 4), rather than at ground level, few large particles were falling out.

Table 5.4. Charcoal concentrations in smoke from a grass fire near Sutton, A.C.T., 13 February, 1979. For locations of samples see Figure 5.8. When sample 4 was collected the densest smoke was overhead, rather than at ground level. Charcoal particles with a diameter greater than about 5μm have been included in the area estimates.

Sample number	Distance from fire front m	Charcoal concentration mm^2/m^3
1	500	33
2	100	22
3	3000	11
4	750	8
5	25	149

Water samples

On 15 February, two days after the Sutton fire, water samples were taken from several farm dams both within and immediately outside the burned area (Figure 5.8). No rain had fallen since the fire, but gusty winds continued. All fresh charcoal in the dams had therefore been carried there in smoke during the fire or blown in soon after. The following day (16 February), water samples were collected from Lake George, Tarago Lagoon and Wingecarribee dam, all of which had smoke carried over them from fires on 13 February (Figure 5.9). Two further samples were taken from farm dams near the Bullio fire (west of Mittagong, Figure 5.9), which was still burning in forested country.

Particles were collected from measured volumes of water (from 20ml to 1000ml, the volume depending on how quickly the filter clogged) on cellulose nitrate membrane filters with a pore size of 5µm, using a hand-operated vacuum pump (Chapter 2). As this was done in the field, only the filters, rather than bulky water samples, needed to be transported. The filters were dried and mounted for microscopic examination as described in Chapter 2. Using a x10 objective, the area of charcoal on each filter was estimated by point counting (Chapter 3.1), between 10,000 and 15,000 points being applied to each sample. Two area estimates were made, one of total charcoal and one of grass charcoal. This was necessary to distinguish, as far as was possible, fresh from older charcoal. Results are presented in Figure 5.10.

Of the water samples from farm dams at Sutton (numbers 1 to 7), only one of the three dams with unburned catchments (2, 3 and 5) had as much fresh grass charcoal as those with burned catchments (1, 4, 6

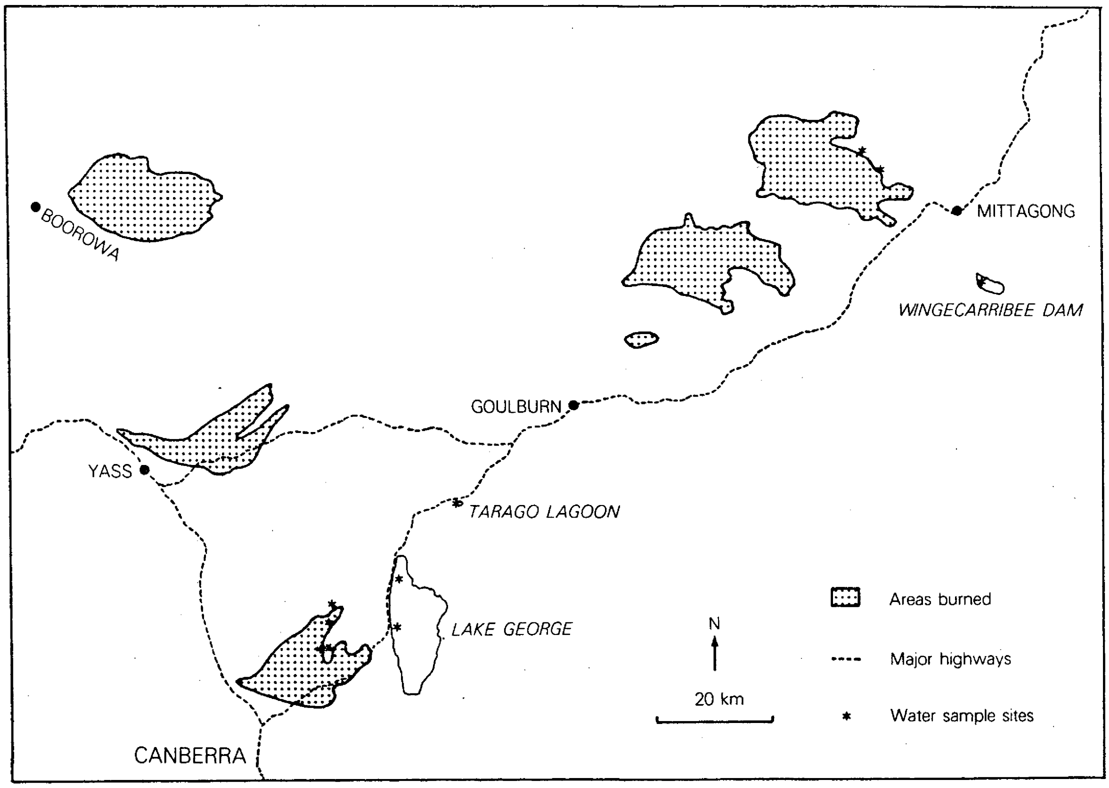


Figure 5.9. Map of part of the Southern Tablelands region of New South Wales showing the major fires which started in the afternoon of 13 February, 1979. Water sampling sites are indicated. Map constructed from fire maps prepared by N.P. Cheney of the CSIRO Division of Forest Research.

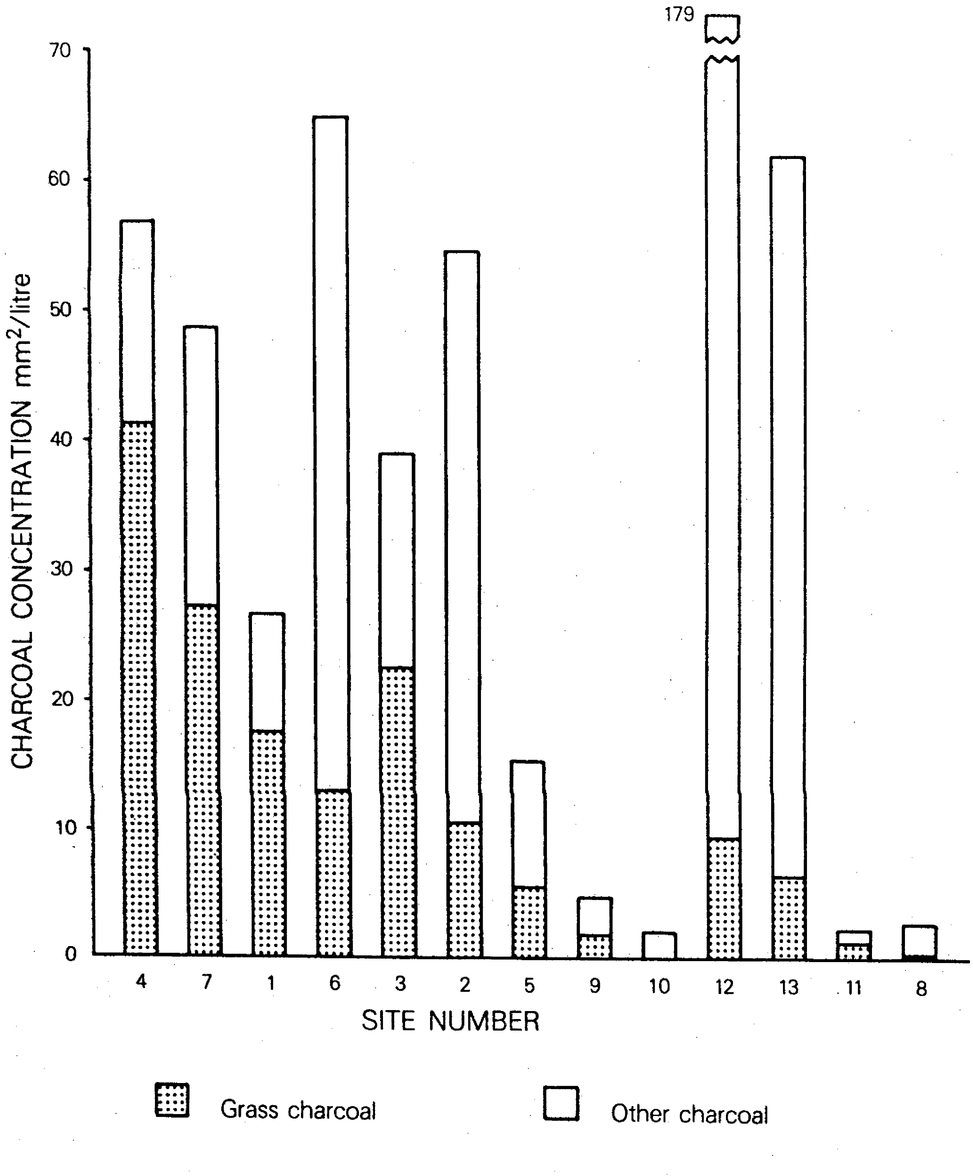


Figure 5.10. Charcoal concentration in water samples from 13 sites. Complete histograms give the total concentrations of charcoal, shaded areas are the proportion which was fresh grass charcoal. Sites 4, 7, 1 and 6 were farm dams in catchments burned in the Sutton fire; sites 3, 2 and 5 were farm dams just outside the area burned in the Sutton fire; sites 9 and 10 were farm dams near the Bullio fire; sites 12 and 13 were at the north-west and south-west of Lake George respectively; site 11 was Tarago Lagoon and site 8, Wingecarribee dam. For locations of sites see Figures 5.8 and 5.9.

and 7). This one (number 3) was about 100m from the edge of the fire, the others (2 and 5) about 200m. The samples from farm dams at Bullio (9 and 10) contained very little charcoal, even though the fire was still burning intermittently about 100m from dam number 10 when the sample was taken. The Lake George samples (12 and 13) contained some fresh grass charcoal which must have fallen out from the Sutton and Yass fires, but there was very little charcoal in water from the two sites furthest from fires, Tarago Lagoon (11) and Wingecarribee Dam (8), each of which was about 37km from the nearest fire.

Fire intensity and wind speed are important determinants of the distance charcoal travels in smoke: dam number 5 was close to and directly ahead of the Sutton fire, but the fire was burning slowly at night when it came closest; although the Bullio fire was burning close to dams 9 and 10, it was flaring only intermittently and not producing dense clouds of smoke at those sites.

The results from both the Rotorod and water samples show that the concentration of airborne charcoal particles decreased rapidly with distance from the fires. This is similar to the pattern observed at the Black Mountain fires (Section 5.2), but measured over much greater distances.

5.5 Bushrangers catchment, 1980

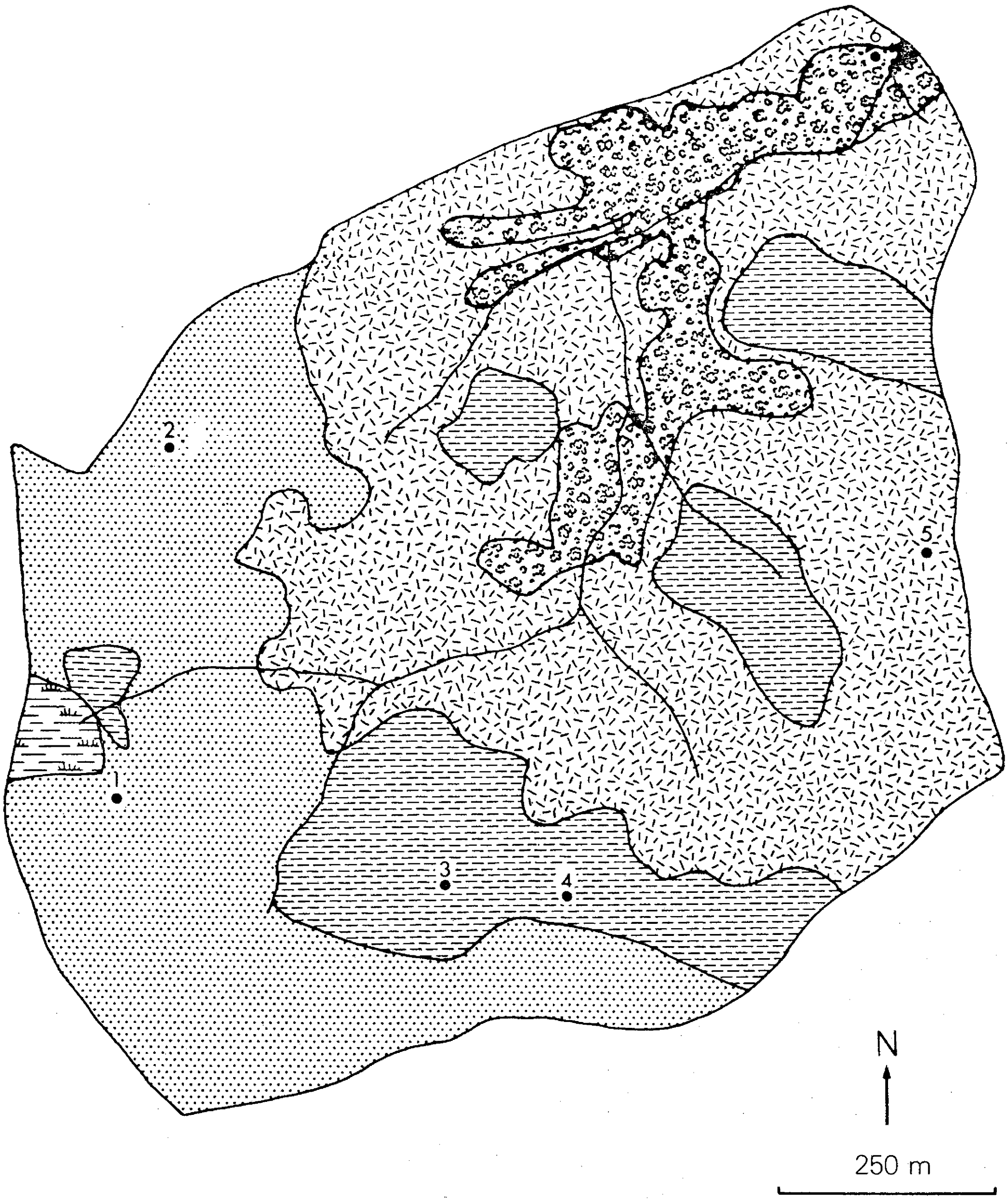
A small catchment at the headwaters of Bushrangers Creek in the Brindabella Ranges, A.C.T. (Figure 5.1), was burned on 19 February, 1980, as part of a hydrological experiment (O'Loughlin, et al., 1982). A standard 90° V-notch weir with an automatic discharge recorder had been installed at the outlet of the catchment in 1967 and an automatic water sampler was added late in 1979. As this was an experimental fire, it was possible to collect samples before, during and after the burn, and to use data and water samples collected by the CSIRO Division of Forest Research.

The catchment

The area of the catchment is 97.5ha with a mean slope of about 11.5°. Mostly shallow, yellow podzolic soils have developed on Silurian granodiorite (Forestry Department, A.N.U., 1973), which outcrops on ridges.

The vegetation consists of sub-alpine woodland in the higher part of the catchment, with dry sclerophyll forests on the lower slopes and wet sclerophyll forest along stream courses. C.J. Lacey (pers. comm.) has mapped the vegetation, recognizing four main types based on the dominant tree species (Figure 5.11). In addition, a *Sphagnum cristatum* bog on the western side and about 20 smaller soaks within the catchment were surrounded or covered by *Leptospermum lanigerum*, *Epacris breviflora* and *Baeckea gunniana*. The dominant trees are *Eucalyptus dalrympleana*, *E.radiata*, *E.dives* and *E.pauciflora*, with *E.viminalis* and some *E.delegatensis* and *E.fastigata* in gullies. Tree heights range up to 43m, but most are less than 30m (O'Loughlin, *et al.*, 1982). Shrubs most common in the dense understorey were *Acacia dealbata*, *A.pravissima*, *Pteridium esculentum*, *Cassinia aculeata*, *Persoonia chamaepeuce*, *Exocarpos stricta*, *Coprosma quadrifida*, *C.hirtella*, *Daviesia ulicifolia*, *Astrotricha ledifolia* and *Lomatia myricoides*, with *Poa sieberana* and *Lomandra longifolia* as the most abundant ground cover species (C.J. Lacey, pers. comm.). Part of the catchment may have burned in 1939, but there is no evidence of any fires since then (O'Loughlin, *et al.*, 1982).

Figure 5.11. Map of Bushrangers catchment showing vegetation distribution and locations of understorey sampling sites. From a vegetation map prepared by C.J. Lacey of the CSIRO Division of Forest Research.



Subalpine woodland (*Eucalyptus pauciflora — E. dalrympleana;* some *E. dives*)

Dry sclerophyll forest (*E. dives — E. dalrympleana*)

Dry sclerophyll forest (*E. radiata — E. dalrympleana;* some *E. pauciflora* and *E. dives*)

Wet sclerophyll forest (*E. viminalis — E. radiata;* some *E. delegatensis* and *E. fastigata*)

Bog (*Sphagnum cristatum, Epacris breviflora, Baeckia gunniana*)

• Understorey sample site

The 1980 fire.

Details of the fire may be found in O'Loughlin, et al. (1982) and are summarized here. In the months preceding the main fire, fuel reduction burns were carried out beyond the perimeter of the catchment. On 19 February, 1980, in high fire danger conditions, the vegetation of the catchment was ignited by dropping 1500 incendiaries in 30 minutes from a helicopter, with some ground lighting along the lower stream course. Ignition commenced at 2.45p.m. and the catchment had burned out by 4.45p.m. The fire removed almost all litter and understorey and scorched the crowns of the trees over 95% of the catchment. The combination of weather conditions and multiple ignition points was chosen to produce strong vertical convection and maximise turbulence within the fire. The area burned in the main fire (120ha) was slightly larger than the catchment.

Changes in the smoke column were monitored by photographs taken every five minutes after 2.55p.m. from Mt Franklin, Mt McDonald and, for the first 45 minutes, from Mt Ainslie (Figure 5.1). The column rose quickly to about 1200m, tilted to the south-east by a north-westerly wind of about 14km/h at the ground surface. Above about 1200m, the smoke was more widely dispersed to the north-east by south-westerly winds of about 35km/h (Figure 5.12). Most particles lifted in the convection column appeared to remain suspended and were dispersed in the atmosphere; no areas of dense fall-out were evident. About 5p.m., when the fire had burned out and there was little vertical convection, westerly winds carried some smoke at low levels across southern Canberra.

Figure 5.12. Smoke from the Bushrangers catchment fire.
(A) from Mt Ainslie, 3.37 pm;
(B) from Mt Franklin, 3.55 pm;
(C) from Mt McDonald, 3.55 pm.
For locations see Figure 5.1.

A

B

C

Surface fuel

The amount of fuel on the ground surface of the catchment before the fire was estimated by the CSIRO Division of Forest Research (O'Loughlin, et al., 1982; N.P. Cheney and P.T. Hutchings, pers. comm.). Litter and twigs less than 3cm diameter were sampled at the intersections of lines on a 100m square grid over the whole catchment, the grid having been positioned by randomly selected starting point and compass direction. At each of the 91 sampling locations litter was sampled using a stratified random sampling scheme (McIntyre, 1952). One litter sample of $0.04m^2$ was taken at random in each of three areas selected as having light, medium or heavy fuel load. Twigs, 0.6-3cm diameter, were separated from other litter, the samples dried at 103°C for about 24 hours and weighed. At every sampling location a 10m line transect was used to estimate the weight of larger fuel (Van Wagner, 1968). The diameters of all branches or logs >10cm diameter on the transect lines were measured, as were those of all twigs or branches 3-10cm diameter on the first 5m of the lines. Specific gravity of the material was estimated by drying and weighing samples. The weight in tonnes of branches and logs per hectare of ground surface was then calculated from:

$$W = 1.234S(\Sigma d^2)/L$$

where W is the weight, S the specific gravity and d the diameter of fuel, and L is the length of the line transect (Van Wagner, 1968; converted for metric units). Twelve 20m line transects were permanently marked and the same method used for determination of fuel quantities both before and after the fire. Results are summarized in Table 5.5, reproduced from O'Loughlin, et al., (1982). The weight of twigs includes estimates of those 0.6-3cm diameter from the litter samples and of those 3-5cm from the line transects.

Table 5.5. Surface fuel in Bushrangers catchment before and after the fire of 19 February, 1980 (from O'Loughlin, et al., 1982).

	Litter	Twigs	Branches 5-10cm	Branches 10-20cm	Branches >20 cm	Total
Pre-Fire Fuel						
fuel mass(t/ha)	16.0	6.5	5.8	13.8	57.4	99.5
fraction(%)	16.1	6.5	5.8	13.8	57.7	100
Post-Fire Fuel						
remaining(t/ha)	0	0	1.5	6.0	42.5	50
consumed(t/ha)	16.0	6.5	4.3	7.8	14.9	49.5
fraction consumed(%)	100	100	74.1	56.5	26.0	49.7

In each of the quadrats harvested for understorey fuel (see below), surface litter on an area 1m x 1m was collected, dried in an oven with fan driven air circulation at 90°C for from 48 to 72 hours and weighed. Each sample included all litter up to about 5cm minimum dimension. Dry weights of the six samples varied from 1471g/m^2 to 3216g/m^2, with a mean of 2400g/m^2, or 24t/ha. This estimate is close to that made by the Division of Forest Research, based on far more samples, of 22.5t/ha for litter and twigs up to 5cm diameter (Table 5.5).

Understorey fuel load

Six 5m x 5m quadrats were selected as being typical, at least one in each vegetation type (Figure 5.11). All understorey and ground cover vegetation, including litter such as bark caught in shrubs, with a minimum dimension less than 6mm, was harvested in each quadrat. Six millimetres is the standard maximum size used to estimate the amount of fine fuel; it is the fine fuels which ignite quickly and carry fires (Luke and McArthur, 1978, p.31). Understorey fuel in each quadrat was harvested in two fractions: the first from 0 to 1m above the ground surface and the second above 1m, the latter class extending to 4m in one quadrat. The fuel was collected in large plastic bags, weighed and dried in an oven with fan-driven air circulation at 90°C for from 12 to 72 hours, with most about 24 hours. Results are summarized in Table 5.6. The mean weight of fine fuel in the understorey was $203g/m^2$ or 2t/ha, giving a total weight for the catchment of 195t.

Table 5.6 Dry weight of fine fuel in the understorey and ground cover vegetation of six $25m^2$ quadrats in Bushrangers catchment. See Figure 5.11 for location of quadrats.

Quadrat	Dry weight of fine fuel, g/m^2		
	0-1m above ground	1-4m above ground	Total
1	102	93	195
2	92	16	108
3	217	17	234
4	130	75	205
5	165	10	175
6	172	128	300
Mean	146	57	203

Charcoal present before the fire

Two samples of the litter and top 2cm of soil were taken from areas 20cm x 20cm from each of three locations in the catchment (Figure 5.13). Organic materials were separated from inorganic by flotation on water and panning, the organic fraction being collected on a 63μm mesh brass sieve. Both fractions were dried at 105°C for 24 hours and weighed. Charcoal was manually separated from the organic fraction and weighed. Results from litter and soil for each sampling area were combined.

The amount of charcoal on the six sampling areas ranged from $12g/m^2$ to $800g/m^2$, with a mean of $280g/m^2$, or 2.8t/ha. The total amount of charcoal remaining in the catchment from previous fires was

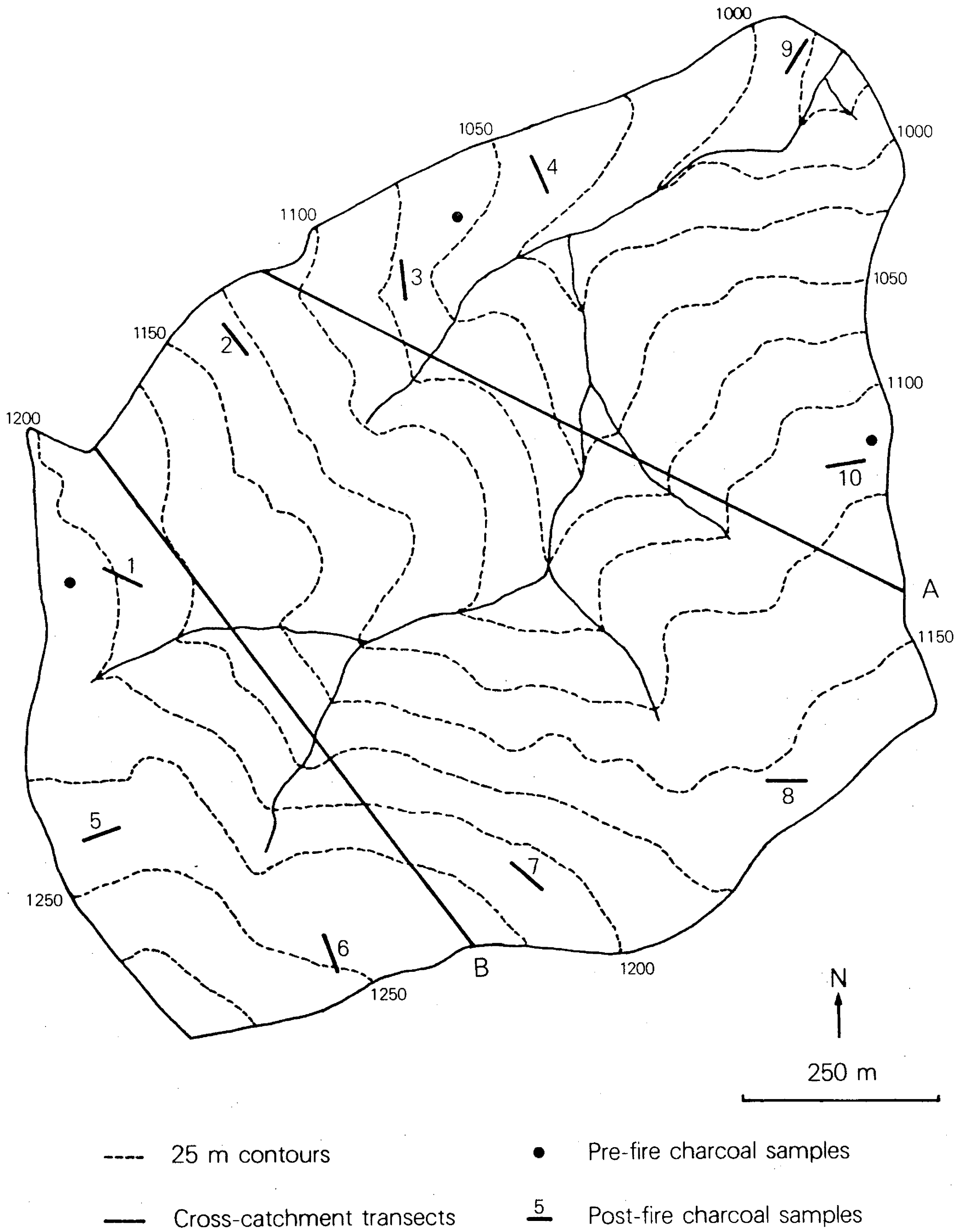


Figure 5.13. Map of Bushrangers catchment showing locations of charcoal samples collected before the fire, of transects used for sampling surface charcoal after the fire and of cross-catchment line transects used for estimating areas of different features.

therefore about 270t. The percentage dry weight of charcoal in the litter ranged from 0.06% to 12.5% and in the soil from 0.17% to 6.1%, while charcoal formed up to 21% of the dry weight of organic matter in litter and up to 23% of that in soil. These figures are underestimates of the amount of charcoal as particles less than about 1mm in length were not separated. It is evident that at least the larger charcoal fragments survive at the ground surface for long periods, in this case at least 41 years. All charcoal fragments had lost sharp edges and were coated with a thin layer of soil, some were incorporated into soil crumbs and a few had fungal hyphae growing around and through them.

Charcoal airborne in smoke

To gain some idea of the distribution of charcoal particles deposited on the ground from smoke around the fire, 228 microscope slides coated with a thin layer of petroleum jelly were placed at distances of from 5m to 3.85km from the edge of the fire (Figure 5.14). Two slides at each location were placed on logs, rocks or the ground surface, one slide close to the roadside and one 5-10m further from the road. Slides were put out between 1p.m. on 17 February and 2.30p.m. on 19 February, and collected between 2p.m. on 20 February and 1p.m. on 21 February. Very light rainfall in the evening of 20 February may have affected the slides along Moonlight Hollow and Mt. Franklin Roads which were not collected until next day. Several slides, particularly those further from the road, had been moved, overturned or could not be found, so were not included in the subsequent analyses.

The total area of charcoal particles per square centimetre on each slide was estimated by point counting (Chapter 3.1). A x10 objective was used and counting continued until 2200 points had been applied to each slide. The identification of large particles was checked using a low-power stereo-microscope. The direct-line distance of each sampling location from the edge and the centre of the fire were calculated from 1:10,000 map sheets (A.C.T. Planning Series, Australian Survey Office). The angle between map grid north and a line joining the centre of the fire and each sampling site was also measured. Aspect and altitude of each site were noted and whether each location had a clear line to the fire or hills intervened.

Results are summarized in Figure 5.14. Significant quantities of charcoal were found on a few slides at some distance from the fire but most, if not all, was probably old charcoal blowing around in dust. Fresh ash and charcoal were observed at three sites to the north-east (Figure 5.14). Only at the edge of the fire was there abundant charcoal, with considerably more on the downwind (south-eastern) edge of the fire than on the upwind edge, even though the slides were only 5-15m from the fire. Because of this difference, it is likely that the charcoal collected on slides close to the fire came from the fire itself and was not charcoal produced by previous burning for fire-breaks.

Apart from the samples around the edge of the fire, no significant correlation was found between the area of charcoal and distance from the edge or the centre of the fire, direction from the fire, altitude, the total time the slides were exposed or the time after the fire they were exposed. The lack of correlations supports the contentions that most charcoal on slides at a distance from

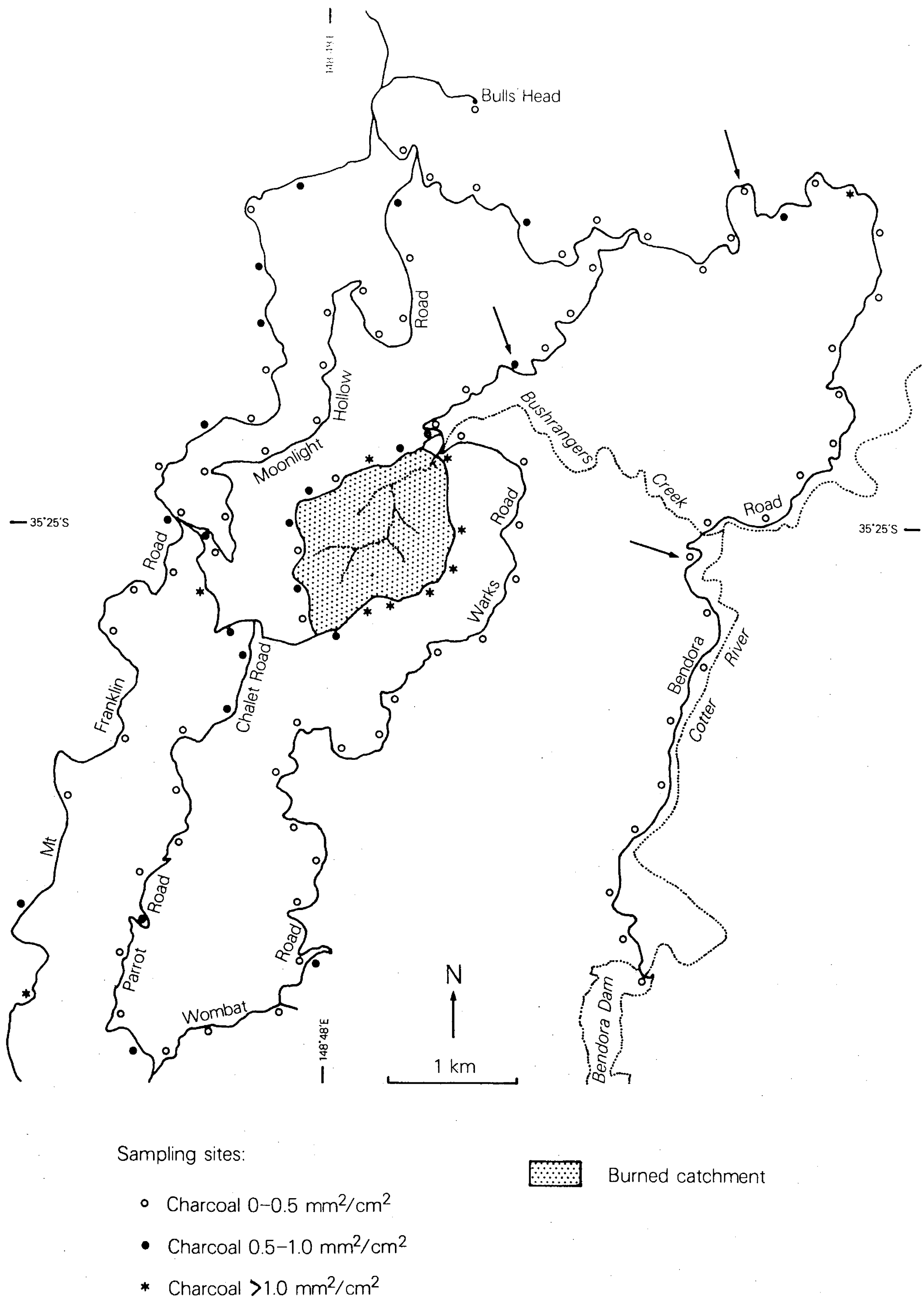


Figure 5.14. Map of the area around Bushrangers catchment showing locations of coated slides. Arrows indicate sites away from the fire edge where fresh charcoal and ash were observed.

Bushrangers catchment did not originate from this particular fire and that the deposition of larger particles from smoke was negligible beyond somewhere between 0.1km and 1km from the fire. The spacing of the samples does not allow greater accuracy in determining this distance. The mean area of charcoal, from whatever source, on all 187 slides was $0.54mm^2/cm^2$, on the 10 slides on the downwind edge of the fire was $3.10mm^2/cm^2$ and on the 177 slides other than those at the downwind edge of the fire was $0.27mm^2/cm^2$. As the collecting efficiency of the coated slides is not known, these figures can only be used as a rough guide.

In addition to this static sampling during the fire, rotating impaction samplers (Rotorods; see Section 5.4) were used to sample particles in smoke at greater distances from the fire. Four samples were taken at sites indicated in Figure 5.1, the first three in the densest smoke found at ground level and the fourth under the main smoke cloud later in the day. Numbers of charcoal particles were counted rather than areas estimated because so few particles were collected (between 20 and 36 on each sampler) that their area was virtually zero. Results are summarized in Table 5.7. It is evident that there were negligible amounts of larger particles in the smoke at some distance from the fire. Again, the collecting efficiency of the petroleum jelly-coated Rotorods is not known, but the amount of charcoal collected, in comparison with samples from the Sutton fire (Section 5.4), does suggest that insignificant amounts of larger particles were carried great distances from the fire. Particles produced by the fire were dispersed in very large volumes of air and deposited over such a large area that their concentration at any one point was very small.

Table 5.7. Results of sampling airborne charcoal particles from the Bushrangers catchment fire with a rotating impaction sampler. For location of sampling sites see Figure 5.1.

Sample number	Distance from fire, km	Time taken	Sampling time, min.	No. charcoal particles per m^3 air
1	22	4.21p.m.	5	104
2	12	4.45p.m.	5	77
3	14	4.59p.m.	5	112
4	25	5.27p.m.	20	35

Using the estimate of Vines, et al. (1971) that less than 2% of fuel burned is carried as particles in smoke, up to 1t/ha of airborne particles would have been produced by the Bushrangers fire, a total of 120t. Of this, about 25% (30t) might have been charcoal ("soot" of Vines, et al., 1971). If this 30t of charcoal were deposited over $1km^2$, the concentration would be $3mg/cm^2$. A conservative estimate of the area on which charcoal was deposited from smoke from Bushrangers catchment might be $1000km^2$, with the concentration of charcoal on the ground surface of $3x10^{-3}mg/cm^2$. Most of these airborne charcoal particles would have been less than 1µm diameter, with very few larger than 5µm (Vines, et al., 1971; Chapter 4). It is thus not surprising that so few larger airborne charcoal particles were detected away from the edge of the fire. If the mean thickness of charcoal particles trapped on the coated slides was 5µm and the density of charcoal $0.8g/cm^3$ (particle density; Humphreys and Ironside, 1980), then the concentration of larger charcoal on the ground at the fire edge would have been about $10^{-2}mg/cm^2$.

The transport of airborne particles from this fire was atypical in that the fire was lit in a particular pattern and under meteorological conditions that minimized potential danger from spot fires in the surrounding forests (O'Loughlin, et al., 1982). A natural fire of equivalent intensity would usually be fast-moving with strong winds behind it and the concentration of charcoal particles at ground level downwind would be higher than that recorded in these experiments, except at the fire edge (cf. Section 5.4). Further, the total area burned (120ha) was far less than that which could be covered in a day by a wild fire (say, 120km^2).

Charcoal in the catchment: (a) on the ground surface

To estimate the amount of charcoal on the ground surface after the fire, ten 50m transects were established, at least one in each vegetation type (Figure 5.13). Using a circular metal litter sampler of 0.04m^2 area, samples were taken every 5m along each transect, giving a total of 100 samples. When the samples were collected, one week after the fire, it was possible to take two fractions: (a) charcoal and remaining litter above the soil surface, and (b) the top 1-2cm of soil. Where there was charcoal below this depth, more soil was taken so that all obvious charcoal on each sample area was included. Samples were collected in plastic bags and weighed in the laboratory. Of the 100 sampling areas, five were excluded as they fell on bare rock, tree trunks or fallen logs.

Transects 1 and 9 were selected for further analysis as their individual samples covered the full range of wet weights, they were in different vegetation types (one in dry sclerophyll forest and one in wet sclerophyll forest), on minimum and maximum slopes and were sampled at the beginning and end of the collection period, respectively. Two samples from transect 9 had been excluded, leaving 18 for analysis.

The organic fraction of each sample was separated from the inorganic by flotation on water and panning, and collected on a 63μm mesh brass sieve. Both fractions were dried at 105°C for 24 hours then weighed. Subsamples of 10-20g of the organic fractions were spread thinly and evenly over an area of about $225cm^2$ on a sheet of paper. Using x10 magnification on a stereoscopic microscope and an advancing stage, the proportions of charcoal, unburnt organics and soil aggregates were estimated by point counting (Chapter 3.1). Charcoal from previous fires, still distinguishable by its coating of soil, was included in the unburnt organic fraction. Points were 0.5cm apart on transects spaced at 2cm intervals and counting continued until at least 200 points had been applied. A better sampling scheme would have had both points and transects at 1cm intervals, but this would have taken twice as long to complete. Two hundred points were sufficient for an accuracy of at least ±10% in the estimate of the proportion of the most abundant component, usually charcoal. Assuming that, as all three components (charcoal, unburnt organics and soil aggregates) floated on water, they all had similar effective densities, then their relative weights would be about the same as their relative volumes. The weight of charcoal in each sample could then be estimated as the product of the proportion of charcoal and the dry weight of the organic fraction.

Although the use of point counting to extrapolate volume directly from projected area is not strictly correct, it was felt to be sufficiently accurate for this particular problem. It was almost impossible to separate smaller particles of the three components manually, some particles were only partially burned and the procedure was extremely slow. Point counting eliminated all these difficulties. To check the validity of the method, three samples were sieved with a

1mm mesh brass sieve. The fraction collected on the sieve was dried and weighed and a point count estimate made as described above of the proportions of the three components. The components were then separated manually and weighed. The point count estimates were found to be well within one standard deviation of the actual weights.

The wet weights of the 95 samples collected from above the soil surface had a skewed normal distribution (lognormal) and a mean of 120g. The wet weights of the corresponding soil samples had a normal distribution and a mean of 462g. The difference in distributions results from the size of the above-ground samples being dependent on the amount of charcoal and litter, while, with some exceptions, approximately the same volume of soil was taken each time.

Samples from transects 1 and 9 had a mean wet weight of 139g for the above-ground fraction and of 484g for the soil fraction. Dry weights of these 36 samples were 92% of the wet weights, the correlation coefficient, r, being 0.9995. Weight loss was due to the removal of particles passing through the 63µm sieve, as well as of water. Water content was low at the time of collection because of both the fire and drought over the preceeding two years. The organic fractions made up 38% of the dry weight of the above-ground samples ($r = 0.9015$), but there was no correlation between organics and dry weight of the soil samples ($r = 0.0327$). Charcoal formed 89% of the dry weight of the organic fraction of above-ground samples ($r = 0.9949$) and 17% of that of the soil samples ($r = 0.7391$). The estimated mean dry weight of charcoal in the above-ground samples was 40g and in the soil samples 13g, the mean total weight of charcoal on the sample areas being 53g.

The most useful correlation was between the total weight of charcoal on each sample area and the wet weight of the above-ground fraction: charcoal made up 36% of the wet weight ($r = 0.8267$). The mean wet weight of all 95 above-ground samples was 120g, so the mean dry weight of charcoal from the 1980 fire on all areas sampled was about 43g, or 1080g/m^2 (11t/ha). The weight of unburnt organics remaining in the above-ground samples from the pre-fire litter less than 2.5cm diameter was about 1t/ha.

In November, 1980, nine months after the fire, a similar set of samples was collected from transects parallel to, but 5m uphill from, the transects established in February. It was hoped that any significant removal of charcoal, by physical, chemical or biological means, would be apparent. By this time the vegetation was regenerating, mainly vegetatively, and a new litter layer was accumulating, consisting mostly of leaves, twigs and bark scorched by the fire but not burned. This litter and any new shoots were removed from each sample area and the top 2cm of soil and charcoal collected, or more if there was obvious charcoal at greater depth. It was impossible to collect a separate above-ground fraction as had been done in February, as charcoal and other organic debris were being incorporated into the soil. All samples were weighed and those from transects 1 and 9 processed as described for the February samples. Only one sample of the 100 collected was excluded and all 20 from transects 1 and 9 were included.

The wet weights of the 99 samples had a normal distribution with a mean of 603g as compared with a mean total wet weight from the sample areas of 582g in February. The mean wet weight of the 20 samples from transects 1 and 9 was 480g and the dry weights were 90%

of the wet weights (r = 0.9979). The mean dry weight of charcoal from the 1980 fire in the sample areas on transects 1 and 9 in November was 43g. This was 9% of the wet weight, but the correlation was not good (r = 0.5398). Using this estimate, the mean dry weight of charcoal in all 99 samples was about 54g, or 1350g/m^2 (13.5t/ha), a figure greater than, but within one standard deviation of, the February estimate. There was thus no apparent decay or removal of charcoal within nine months after the fire, at least away from streams and wet areas.

Combining the estimates from February and November, the mean dry weight of charcoal remaining on the ground was about 12t/ha, excluding areas of bare rock, tree trunks or fallen branches or logs.

Charcoal in the catchment: (b) on logs and trees

Much of the charcoal produced by the fire remained on or around partially burned fallen branches and trunks or on standing trees. Twelve fallen branches and logs were chosen to estimate the amount of charcoal remaining attached to the larger fuel. Mean diameters ranged from 2.8cm to 91.3cm and lengths from 0.95m to 15.15m. Each branch or log was sampled at 1m intervals or, for the two smallest, at 45cm intervals, by cutting through the charcoal to the wood with a chainsaw. The smaller branches were cut through, the larger logs incised at four points, and the depth of charcoal measured at the top, base and two sides of each section. The largest log could not be rolled over with the equipment at hand, so measurements were made as near to the base as possible where the undersurface was above the ground, or assumed zero where lying on soil. Dimensions were noted of sections burned out and of branching. The volume of charcoal on each 1m length (or less where appropriate) was estimated as the product of mean depth of charcoal, perimeter and length of section, and these estimates were added to give the total volume of charcoal on each branch or log. The area projected by each branch or log on the ground surface was estimated as the product of mean diameter and length, and the volume of charcoal per unit area of ground surface was then the total volume of charcoal divided by the projected area. The mean depth of charcoal on each branch or log was also calculated.

Results are summarized in Table 5.8. As the volume of charcoal per unit area of ground surface is independent of the size of the branch or log, the mean of the twelve estimates may be used as the average of all such branches and logs; this is 2.31cm^3/cm^2. Assuming the density of charcoal to be about 0.8g/cm^3 (Humphreys and Ironside, 1980), the weight of charcoal on logs and branches was about 1.85g/cm^2 of ground surface.

Table 5.8. Charcoal quantities on twelve partially burned fallen branches or logs, Bushrangers catchment.

Branch or log		Charcoal		
Mean diameter cm	Length cm	Mean depth on branch cm	per unit area of ground surface Volume cm^3/cm^2	Weight g/cm^2
2.80	95	0.53	1.48	1.18
4.63	164	0.61	1.82	1.46
8.08	440	0.73	2.28	1.82
8.17	282	0.77	2.41	1.93
8.96	829	0.76	2.40	1.92
9.65	382	1.10	3.35	2.76
16.54	634	0.59	1.87	1.50
16.99	795	0.55	1.74	1.39
32.75	623	0.52	1.65	1.32
35.04	540	0.82	2.58	2.06
39.93	756	1.41	4.43	3.54
91.31	1515	0.51	1.61	1.29
	MEAN:	0.74	2.31	1.85

No measurements were made of the amount of charcoal remaining on standing trees and shrubs. This was extremely variable for several reasons: (a) flames are carried to greater heights by stringy bark than by smooth bark; (b) the height and depth to which bark burns depend also on flame height and fire intensity, which in turn depend on the fuel at the base of each tree; (c) the height and depth to which understorey branches burn depend similarly on local fuel; (d) new fire scars formed and old scars burned further, creating large amounts of charcoal in some trees; and (e) some hollow trees acted as chimneys, burning out the core to heights of several metres.

An approximation can be made by assuming all trees had a layer of charcoal up to 1m height and of the same depth as that on fallen logs (7mm). The diameters at breast height of 136 trees along the two cross-catchment transects (see below) were measured and the mean was 27cm. The total volume of charcoal on a tree of average diameter would then be about $6000cm^3$ and the basal area, assuming a basal diameter of 30cm, about $700cm^2$. The equivalent volume of charcoal per unit area of ground surface (trunk space) would be about $8.6cm^3/cm^2$ and its weight about $7g/cm^2$.

The amount of fuel less than 6mm diameter in the understorey was estimated above as 2t/ha and it is assumed that all of this was consumed in the fire. Van Loon (1977), sampling the understorey of forests in the Blue Mountains, N.S.W., comparable with the Bushrangers catchment, found that 60% of the weight of the understorey was 0-6mm diameter and 40% was 6-25mm diameter. He excluded from these calculations stems over 25mm diameter; at Bushrangers, stems over 25mm diameter were included as trees. If 60% of the understorey weighed 2t/ha, then 40% weighed 1.3t/ha. Assuming half of this weight was consumed in the fire and half the remainder was charcoal, the weight of charcoal on understorey stems and branches would have been about 0.3t/ha.

Areas of catchment surface occupied by different features

To estimate the total amount of charcoal in the catchment it is necessary to know the areas of surface occupied by different features, such as bare rocks, fallen branches and logs or the trunk space of trees. Two transects across the catchment were established by starting point and compass bearing to include all vegetation types and geomorphological features (Figure 5.13). Measuring tapes were laid on the ground along each transect and the metre marks on the tapes used to define points on the ground surface. The nature of the surface at each point was noted, in the following categories:

R: bare rock

UB: unburnt

T: trees

Lb: branches and logs fallen before the fire

La: branches and logs fallen after the fire

N: with normal amount of charcoal

C: with large amount of charcoal from burnt branches.

The proportion of the total area falling within each of these categories was then estimated from the ratio of the number of points in each category to the total number of points (Chapter 3.1). The areas occupied by each feature within the catchment could then be calculated. Results are presented in Table 5.9.

Table 5.9. Areas within Bushrangers catchment occupied by different surface types after the fire. For locations of transects see Figure 5.13. R = bare rock, UB = unburnt, T = trees, Lb = logs fallen before the fire, La = logs fallen after the fire, N = normal amount of charcoal, C = large amount of charcoal.

Transect	R	UB	T	Lb	La	N	C	Total
A (900m)								
Points	59	12	6	28	1	711	83	900
%	6.56	1.33	0.67	3.11	0.11	79.00	9.22	100
B (750m)								
Points	63	15	10	38	6	548	70	750
%	8.40	2.00	1.33	5.07	0.80	73.07	9.33	100
A+B (1650m)								
Points	122	27	16	66	7	1259	153	1650
%	7.39	1.64	0.97	4.00	0.42	76.30	9.27	100
AREA(ha)	7.2	1.6	0.9	3.9	0.4	74.4	9.0	97.5
S.D.	$\pm$0.63	$\pm$0.31	$\pm$0.23	$\pm$0.47	$\pm$0.16	$\pm$1.02	$\pm$0.70	

Using these areas and estimates obtained in preceding sections of the amount of charcoal per unit area of ground surface, the total amount of fresh charcoal in the catchment after the fire may be calculated:

bare rock:	0
unburnt:	0
fallen branches and trunks (185t/ha; 3.9 ha):	720 t
standing trees (700 t/ha; 0.9 ha):	630 t
other ground surface (12 t/ha; 84 ha):	1010 t
understorey shrubs (0.3 t/ha; 84 ha):	25 t
TOTAL:	2385 t

The mean weight of fresh charcoal in the catchment was therefore about 24.5t/ha (245g/m^2).

The amount of fuel in Bushrangers catchment before the fire was 99.5t/ha, of which 50t remained after the fire (Table 5.5). In addition, about 1t/ha of litter remained unburned. The CSIRO estimate of remaining fuel includes the weight of charcoal on branches and logs (N.P. Cheney, pers.comm.), so this weight (7t/ha) must be subtracted from the total. The adjusted estimate of unburned fuel is then 44t/ha and of fuel consumed 55.5t/ha. The amount of charcoal produced in the fire was 24.5t/ha, or 44% of the fuel burned. This figure is the same as that of average yield of charcoal from fourteen Eucalyptus and one Melaleuca species at a carbonization temperature of 400°C in laboratory experiments cited by Humphreys and Ironside (1980).

About 24.5t/ha of charcoal remained in the catchment after the 1980 fire, as well as about 3t/ha of charcoal from previous fires, the last of which was in 1939. If all the charcoal in the catchment before the 1980 fire was produced in the 1939 fire and the same amount of charcoal was produced by both fires, then about 21.5t/ha of charcoal disappeared in 41 years, an average of 0.5t/ha/y ($5mg/cm^2/y$).

Waterborne charcoal

The main deposition site for waterborne sediments from the Bushrangers catchment is the Cotter Dam, about 20km downstream (Figure 5.1). As the area burned is so small in proportion to the whole Cotter catchment and the distance between Bushrangers catchment and the Cotter Dam is large, it would be very difficult to find in the Cotter Dam sediments a layer of charcoal attributable to this particular fire. To estimate the amount of charcoal carried downstream from the burned catchment, the charcoal content of water flowing through the weir at the base of the catchment was monitored over sixteen months after the fire.

Water was collected by an automatic water sampler installed by the CSIRO Division of Forest Research, with the intake suspended 25cm below a raft floating in the centre of the weir. Most of the samples were taken during rainfall events when the sampler was usually set to operate after each one inch (2.54cm) change in water level, either rising or falling. It was expected that the time each sample was taken would be recorded so that the corresponding discharge rates would be available from the continuous water level recorder. Times were recorded for most of the post-fire samples, but not for those collected before the fire.

The weight of suspended sediment and the amount of charcoal in subsamples of the water collected were estimated as follows. Cellulose nitrate membrane filters with a pore size of 5μm were numbered, dried in an oven at 60°C and weighed. Using the filtration apparatus described in Chapter 2, suspended sediment was collected from the water samples on the filters, which were again dried and weighed. The volume of water passed through each filter was measured and varied from 11ml to 135ml, with most between 50ml and 100ml. An estimate of the weight of suspended sediment per unit volume of water could then be calculated. The filters were cleared and mounted on microscope slides (Chapter 2) and point count estimates made of the area of charcoal on each (Chapter 3.1). A x10 objective was used and counting continued until 3000-5000 points had been applied to each sample, with most about 4000. An estimate of the area of charcoal per unit volume of water was then calculated.

The full data set should have consisted of concentrations of charcoal and suspended sediment, times and dates of sampling and discharge rates. A continuous record of all these variables through all rainfall events over sixteen months after the fire was not available for several reasons: (a) samples were not collected in all rainfall events; (b) samples taken over the first three months after the fire were inadvertently discarded at CSIRO; it is not known whether this gap in the data is important (cf. Section 5.3), but there was only one significant rainfall event in that time; (c) discharge rates were not available for some samples when the time of collection had not been recorded (no discharge rates were available for pre-fire samples); (d) for estimates of the weight of suspended sediment in the early samples, it was assumed that the weight of the cellulose nitrate filters varied little around their mean weight; this variation proved to be significant in relation to the small sediment weights, leading to inaccurate estimates; (e) three sets of samples had not been shaken before subsamples were removed for water chemistry analyses at CSIRO; the concentrations of charcoal and suspended sediment were thus too high (it is suspected that this might have occurred with the pre-fire samples also); and (f) algae had grown in some samples, in spite of refrigeration, so estimates of sediment weight were likely to be too high. Excluding these, the numbers of samples with acceptable estimates of different parameters were: (a) charcoal area, 205; (b) sediment weight, 143; (c) discharge rate, 185; (d) charcoal area per unit weight of sediment, 218; (e) charcoal area and discharge rate, 119; and (f) sediment weight and discharge rate, 87. The last were the only samples for which all parameters were known.

Charcoal concentrations in pre-fire samples ranged from 18 to 989mm^2/litre, with a mean of 219mm^2/litre (n = 29), and in post-fire samples from 10 to 3316mm^2/litre, with a mean of 353mm^2/litre (n = 176). As mentioned above, the estimates for pre-fire samples might be too high. Unlike the water samples from Eden catchment 4 (Section 5.3), there was a significant increase in mean charcoal concentration after the fire, but the largest increase at both sites occurred during the most extreme rainfall events.

It was expected that the concentration of charcoal, corrected for discharge rate, would decrease over time after the fire as vegetation regenerated, a new litter layer formed and charcoal on wet areas was depleted. Several data analyses were used to test this assumption:

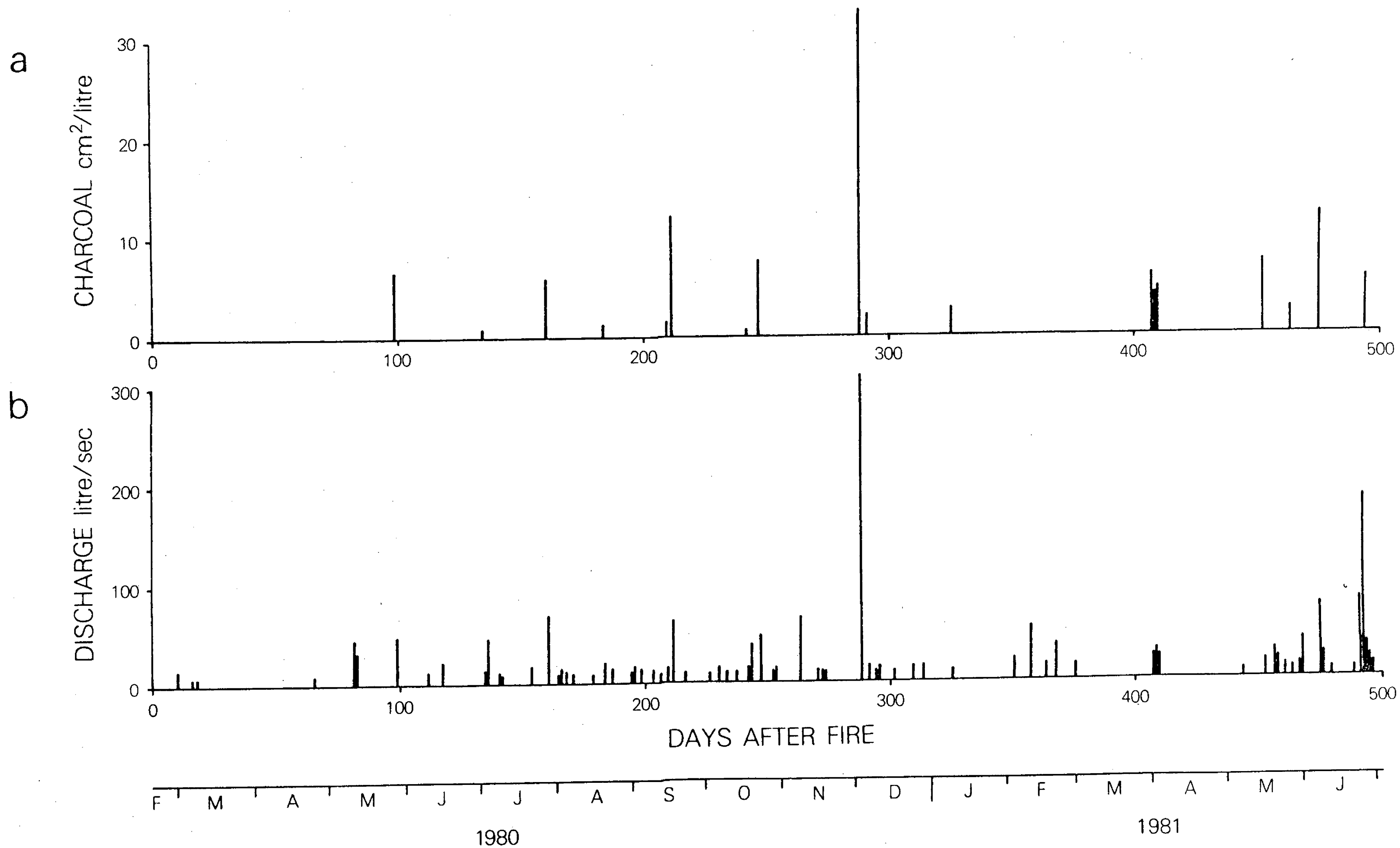
(1) Figure 5.15 shows maximum discharge rates of water through the weir for all but the most minor rainfall events over the sixteen months following the fire, along with maximum charcoal concentrations in the events which were sampled. While there is some correspondence between maximum amount of charcoal and maximum discharge, the relationship varies and shows no consistent trend over time. The correlation coefficient (r) of the regression between these variables is 0.9377 for all 16 samples, but only 0.6786 if the exceptionally large values in the event 288 days after the fire are excluded (n = 15).

(2) Over all samples in all events there was some correlation between the amount of charcoal and discharge rate (r = 0.5651, n = 119) and between the amount of suspended sediment and discharge rate (r = 0.7005, n = 87).

(3) The concentrations of charcoal and suspended sediment did not decrease over time after the fire; there was as much variation within rainfall events as between them.

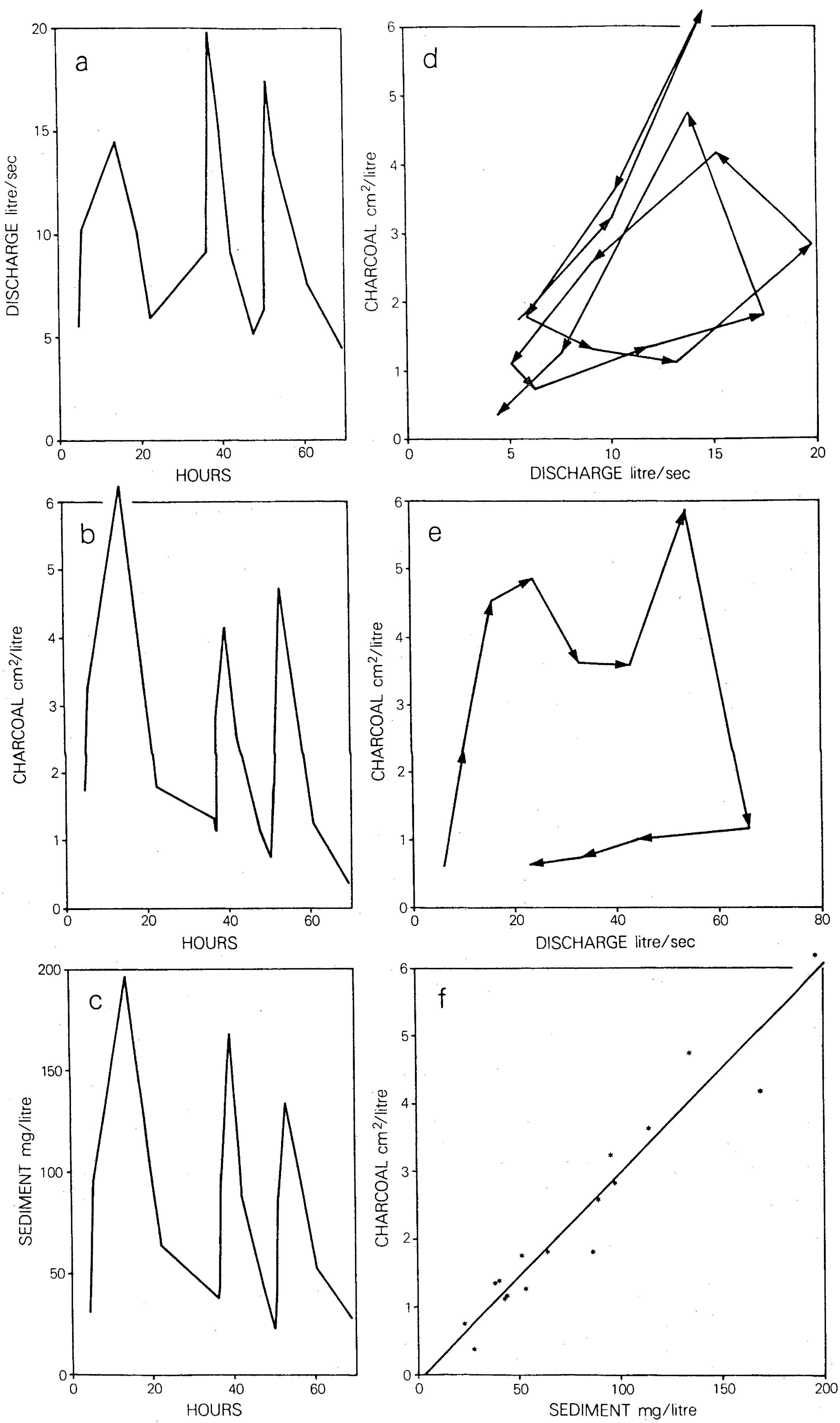
(4) There was no correlation between the number of days after the fire and the ratio of charcoal concentration to discharge rate (r = 0.1896, n = 119), nor between the number of days after the fire and the ratio of sediment concentration to discharge rate (r = 0.2205,

Figure 5.15. (a) Maximum charcoal concentrations in water sampled during rainfall events over sixteen months following the Bushrangers catchment fire. (b) Maximum discharge of water through the weir for all but the most minor rainfall events over sixteen months after the fire.



a
CHARCOAL cm²/litre
30
20
10
0
0
100
200
300
400
500
b
DISCHARGE litre/sec
300
200
100
0
0
100
200
300
400
500
DAYS AFTER FIRE
F
M
A
M
J
J
A
S
O
N
D
J
F
M
A
M
J
1980
1981

Figure 5.16. Changes in discharge and concentrations of charcoal and suspended sediment through individual rainfall events after the Bushrangers fire. a, b, c, d and f: rainfall 407-409 days after the fire; e: rainfall 160 days after the fire. Arrows on d and e connect samples in sequence.



a
DISCHARGE litre/sec
HOURS
b
CHARCOAL cm²/litre
HOURS
c
SEDIMENT mg/litre
HOURS
d
CHARCOAL cm²/litre
DISCHARGE litre/sec
e
CHARCOAL cm²/litre
DISCHARGE litre/sec
f
CHARCOAL cm²/litre
SEDIMENT mg/litre

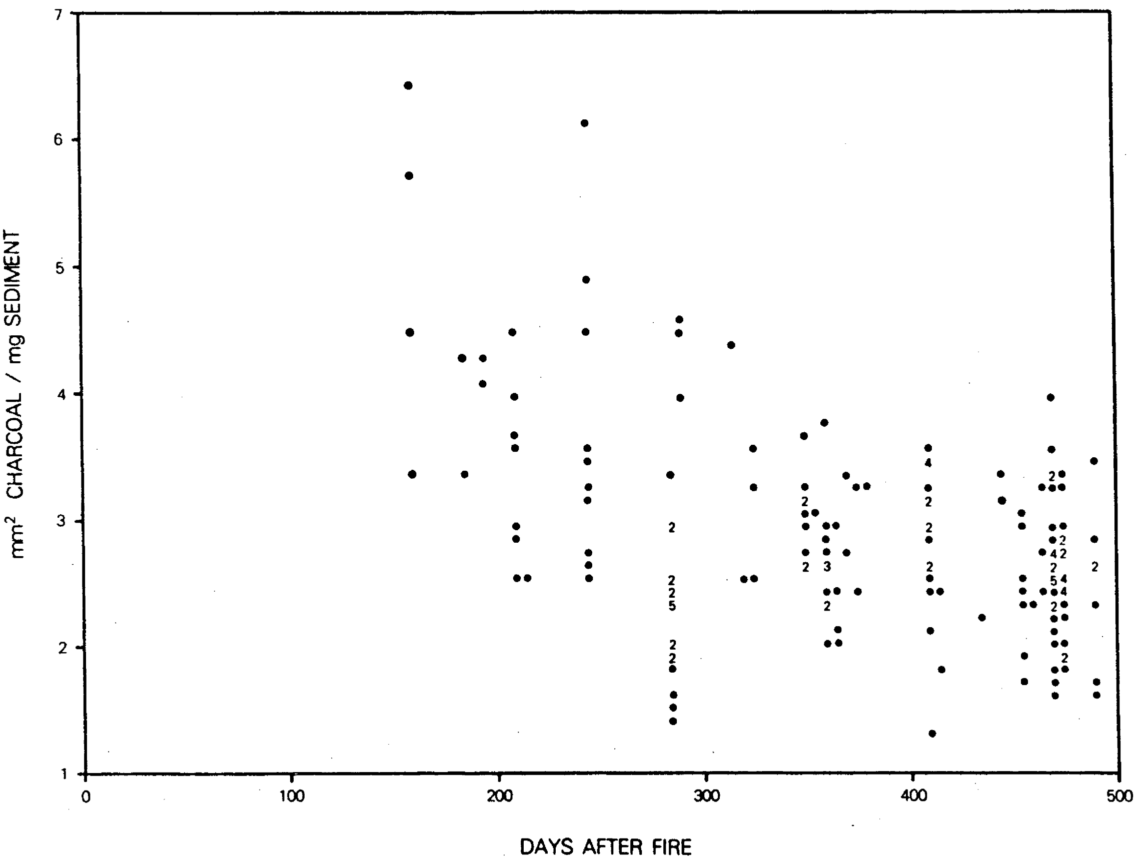


Figure 5.17. The area of charcoal per unit weight of sediment in all water samples plotted against the number of days after the Bushrangers fire ($n = 172$, $r = -0.4350$).

proportion of charcoal over time after the fire, a trend similar to that observed by Blong, et al. (1982).

Although many of the correlations given above are statistically significant, the regressions show no unequivocal trends in the data over sixteen months after the fire. The effects of vegetation regeneration on sediment supply are not apparent. The data do suggest that charcoal input to a sedimentary basin from any one fire might be attenuated over many years. Until the hydrological complexities of catchments are better understood, it will be impossible to predict the amount of charcoal washing off a particular catchment under different rainfall regimes.

Over all samples for which both charcoal concentration and discharge rate were known (n = 119), mean charcoal concentration was $238mm^2$/litre and mean discharge rate 19.34 litres/second. Over those samples for which both sediment concentration and discharge rate were known (n = 87), mean sediment concentration was 92mg/litre and mean discharge rate 18.96 litres/second. The total volume of water which passed through the weir during the sampling period, from the date of the fire (19 February, 1980) to 30 June, 1981, was 187×10^6 litres and the mean discharge rate 4.34 litres/second. Using correlations determined from the samples, the concentration of charcoal in water flowing through the weir at this discharge rate would be about $140mm^2$/litre, with sediment concentration about 44mg/litre. Over the sixteen month period after the fire about $26{,}180m^2$ of charcoal passed through the weir and about 8230kg of suspended sediment. If the charcoal particles had a mean thickness (minimum dimension) of 5μm and a density of $0.8g/cm^3$ (particle density; Humphreys and Ironside, 1980) then the total weight of suspended charcoal washed off the catchment over sixteen months would have been about 100kg. Because of the large errors from sampling and estimation methods, these figures may be used as a rough guide only. Further, large charcoal fragments in the bed load of the stream are not included, nor do the estimates take account of the exceptionally high sediment and charcoal concentrations likely to have occurred in the first rainfall events after the fire (cf. Section 5.3).

Conclusion

Far greater amounts of charcoal remained in the catchment than were removed in smoke or runoff over sixteen months after the fire. Charcoal concentration in water flowing from the catchment increased with discharge rate, but the only time substantial quantities were washed away was during the most intense rainfall. The years preceding the fire, and the entire sampling period, were exceptionally dry; with normal soil moisture conditions and rainfall, much more sediment and charcoal would have been eroded from the catchment. It is likely that each rainfall event for many years will remove charcoal, but both soil and charcoal will become less erodible as vegetation regenerates and litter accumulates. Because of the low rainfall, the amount of charcoal from this fire deposited in sediments might be similar to that from a less intense fire at a time of normal rainfall.

The amount of charcoal falling out from smoke decreased rapidly with distance from the fire, the only significant amounts being found at the edge of the fire. No decrease in sediment or charcoal concentrations of water flowing from the catchment was detectable over sixteen months after the fire, principally because there was as much variation within as between events. Charcoal and suspended sediment concentrations correlated well, and the charcoal fraction of the sediment decreased with time after the fire.

5.6 Further observations and conclusions

The observations described in this chapter of the distribution of charcoal around present-day fires would have been greatly enhanced by measurements of the amount of charcoal deposited in sediments from the fires studied. It was thought unlikely that charcoal from the Bushrangers catchment fire would be detectable in the Cotter Dam sediments (Section 5.5), but it was possible that charcoal from the Sutton and Yass fires (Figure 5.9) might be deposited in a weir on the Yass River at Yass, and that charcoal from the two fires west of Mittagong (Figure 5.9) might be deposited in Lake Burragorang, downstream along the Wollondilly River. Frozen cores (Wright, 1980; Rymer and Neale, 1981) were taken of the top 30-50cm of sediments in Yass Weir and Lake Burragorang 1 week and 1, 3, 6, 9 and 32 months after the fires. Further frozen cores were taken of the top few centimetres of sediment in seven small farm dams near Sutton, some in burned catchments and some outside the burned area, but which would have collected fall-out from smoke. These cores were taken two weeks after the fire, before any substantial rainfall, and the coring was repeated in the same dams 8-10 weeks later, after rainfall. These experiments were not successful for two reasons: (a) the freeze-corer seriously disturbed the surface sediments; and (b) severe drought conditions prevailed in the years following the fires. On the first visit to Lake Burragorang (22 February, 1979) cores were taken in 4m of water; on the last visit (18 December, 1980) the core site was dry and the stored water was 2km downstream. These monitoring experiments should be repeated with more appropriate equipment and more favourable weather.

Rainfall of 36mm fell in the Bullio area, west of Mittagong, three weeks after the fire. Litter, including charcoal, was washed over the ground surface but collected behind all obstructions. There was thus much redistribution of charcoal but it is not known how much was actually removed from the catchment. In the first significant rainfall event after the Sutton fire, charcoal collected at the base of a steep, smooth slope that had been completely covered by pasture. The charcoal formed a layer several centimetres thick and about 200 square metres in extent. This was the only place such an accumulation was observed and was due to blocking of drainage by road construction.

One further observation is of significance to the interpretation of sedimentary records. Much charcoal accumulated in cracks in clay drying at the edges of dams. When the clay was rewet the cracks closed, trapping charcoal below the surface, sometimes underneath plates of clay which had separated when dry. While the vertical cracks might be recognizable in sediment cores, the horizontal layers of charcoal, one or more centimetres below the sediment surface at the time of a fire, would give the impression that the fire occurred some years earlier.

The range of values of the amounts of charcoal transported by wind or water in the collections described in this chapter are listed in Table 5.10. The background of charcoal in the air, even from extensive wildfires in the region, is low compared with the amount of airborne charcoal at the edge of fires. By far the greatest amounts of charcoal are transported by water during rainstorms after fires. These figures will be compared with those from fossil samples in Chapter 8.

Table 5.10. Summary of results of collections of charcoal transported from present-day fires. Numbers 5.1 to 5.5 refer to the sections in which the data is described.

Background airborne:	5.1	2-10 $mm^2/cm^2/y$	Includes urban input in Canberra
Airborne on slides:	5.2	101-935/cm^2	10-80m from fires
	5.5	0-10mm^2/cm^2	5m-4km from fire
Airborne on Rotorods:	5.4	8-149mm^2/m^3 air	25m-3km from fire
	5.5	35-112/m^3 air	12km-25km from fire
Airborne in dams:	5.4	0-41mm^2/l water	0-37km from fires
Waterborne:	5.3	$1.8x10^5$-$1.7x10^8$/l water	
	5.3	0-313mm^2/l water	
	5.5	13-3316mm^2/l water	
	5.3	$1.2x10^4$-$1.9x10^5$/mg suspended sediment	
	5.3	0-27mm^2/mg suspended sediment	
	5.5	1-7mm^2/mg suspended sediment	

Most charcoal produced by fires remains on the ground or attached to standing vegetation. Fine particles and some larger ones may be moved immediately by wind or water, but the bulk remains as "slow-release" charcoal which is broken down over time by physical, chemical and biological processes. More charcoal is transported by water than by wind. The strong convection currents created by a fire can lift large charcoal fragments and carry them great distances, but this is a single event. Every rainfall event over some years after a fire has the potential to transport charcoal to a sedimentary basin. How much charcoal is removed in each rainfall event will depend on antecedent soil moisture conditions and the timing and intensity of rainfall in relation to vegetation regeneration and litter accumulation. If a fire is followed by drought, very little or no charcoal might reach a sedimentary basin. Relatively small quantities of charcoal are transported short or long distances by wind. This is a continuous process as charcoal is probably a constituent of soil and dust over most of the Australian continent.

The main source area for charcoal deposited in a lake is, as suggested in Chapter 4, the water catchment of that lake. Significant quantities of charcoal might also be deposited in a lake from outside its catchment if a fire were close by, with the wind blowing directly over the lake. As charcoal is carried from its source, its concentration falls as particles are dispersed in greater volumes of air or water or settle out from the supporting medium. The further charcoal has to travel from the source to a lake, the less likely it is to get there and, with waterborne charcoal, the more attenuated will be the input of charcoal to sediments.

Chapter 6

INTERPRETATION OF THE SEDIMENTARY CHARCOAL RECORD

The assumption fundamental to reconstructions of fire history from fossil charcoal in sediments is that the amounts of microscopic charcoal in pollen or other preparations reflect past fires. A similar assumption is made when reconstructing vegetation history from the pollen record. Many difficulties with relating charcoal to fires are similar to those with relating pollen to vegetation (M.B. Davis, 1963; R.B. Davis, 1967; Oldfield, 1970; Birks and West, 1973; Faegri and Iversen, 1975), but others are unique to the charcoal record. The most important differences between pollen and charcoal representation are discussed below, followed by consideration of factors affecting the amount of charcoal deposited in sediments and of the effects of sediment sampling schemes on interpretation of fire history.

Charcoal and pollen representation

It has been shown (Chapters 4 and 5) that most charcoal deposited in sediments is likely to have been transported by water rather than wind. The main charcoal catchment of any lake is its water catchment, with a little input from outside this area. The likelihood of airborne charcoal reaching a lake from a fire will fall off sharply with distance. The charcoal catchment may or may not be the same as the pollen catchment, but different mechanisms of production, dispersal and transport of pollen and charcoal may make it difficult to find, in the sedimentary record, distinct correspondence between individual fires and resultant vegetation changes. In addition, only part of the pollen or charcoal catchment might be burned in any one fire.

Most of the charcoal produced by a fire remains on the ground (Chapter 5.5) in fragments ranging in size from less than a micrometre to several centimetres long. Depending on soil moisture content, rainfall intensity and vegetation and litter cover, larger charcoal fragments may be washed into streams with the smaller ones and eventually carried to deposition sites. Following any fire, the processes of breakdown of charcoal, its transport, deposition, resuspension, further breakdown and redeposition may continue for many years, so that input into a sedimentary basin might take place over a very long time (Chapter 4). The same processes may continue in a sedimentary basin, with physical and biological mixing of sediments (R.B. Davis, 1967) and, possibly, further breakdown of charcoal by compaction of sediments, changes in the chemical environment or microbial activity. The degree of weathering of individual particles may give some indication of their history: fresh charcoal fragments have sharp edges and, often, fine projections, and may retain obvious cellular structure; weathered fragments are smoother and rounder than fresh charcoal particles.

Charcoal fragments are produced and transported in a wide range of sizes, while most pollen grains are silt-sized, with diameters between 10µm and 100µm. If water-sorting of suspended particles leads to spatial distribution of different sizes of particles within a sedimentary basin, only a proportion of the charcoal will be deposited with the pollen; larger and smaller fragments will collect elsewhere. Some pollen is transported in whole anthers or flowers, but most is probably carried as individual grains that are very resistant to physical, chemical and biological breakdown. Charcoal fragments are brittle and may be almost infinitely subdivided. Pollen and charcoal are thus affected very differently by procedures used to prepare sediment samples for examination: most pollen grains remain intact, while charcoal may be broken down or removed (Chapter 2).

From the morphology of a pollen grain, it is usually possible to identify the family, genus or species of plant that produced it. In the size range encountered in pollen preparations, most charcoal particles are fragments of cell walls, whole cells or aggregates of a few cells. The only distinguishable particles are those with cell wall structures unique to one taxon or, more commonly, carbonized epidermal or cuticular fragments retaining characteristic cell shapes and stomatal structures. Many samples contain charred fragments of monocotyledon epidermis or cuticle and, using appropriate reference material, it should be possible to identify the genus or species from which they came (Livingstone and Clayton, 1980). Separate estimates of the amount of monocotyledon or grass charcoal and of charcoal from unknown sources, might be useful in some circumstances (e.g., Chapter 5.4).

The amount of charcoal in sediments

The most important difference between the pollen and charcoal record from sediments is that fires are discrete, short-term events, often of only a few hours duration and at intervals of many years, while, at the usual level of resolution of pollen analyses, pollen production may be regarded as continuous. The pattern of input of charcoal to sediments over time is thus very different from that of pollen. The amount of charcoal deposited in a sedimentary basin after any one fire depends on many factors. The most important of these, and their interdependence, are summarized in Figure 6.1. Ideally, the amount of charcoal deposited after a fire should be directly proportional to the amount of charcoal produced, while comparison of

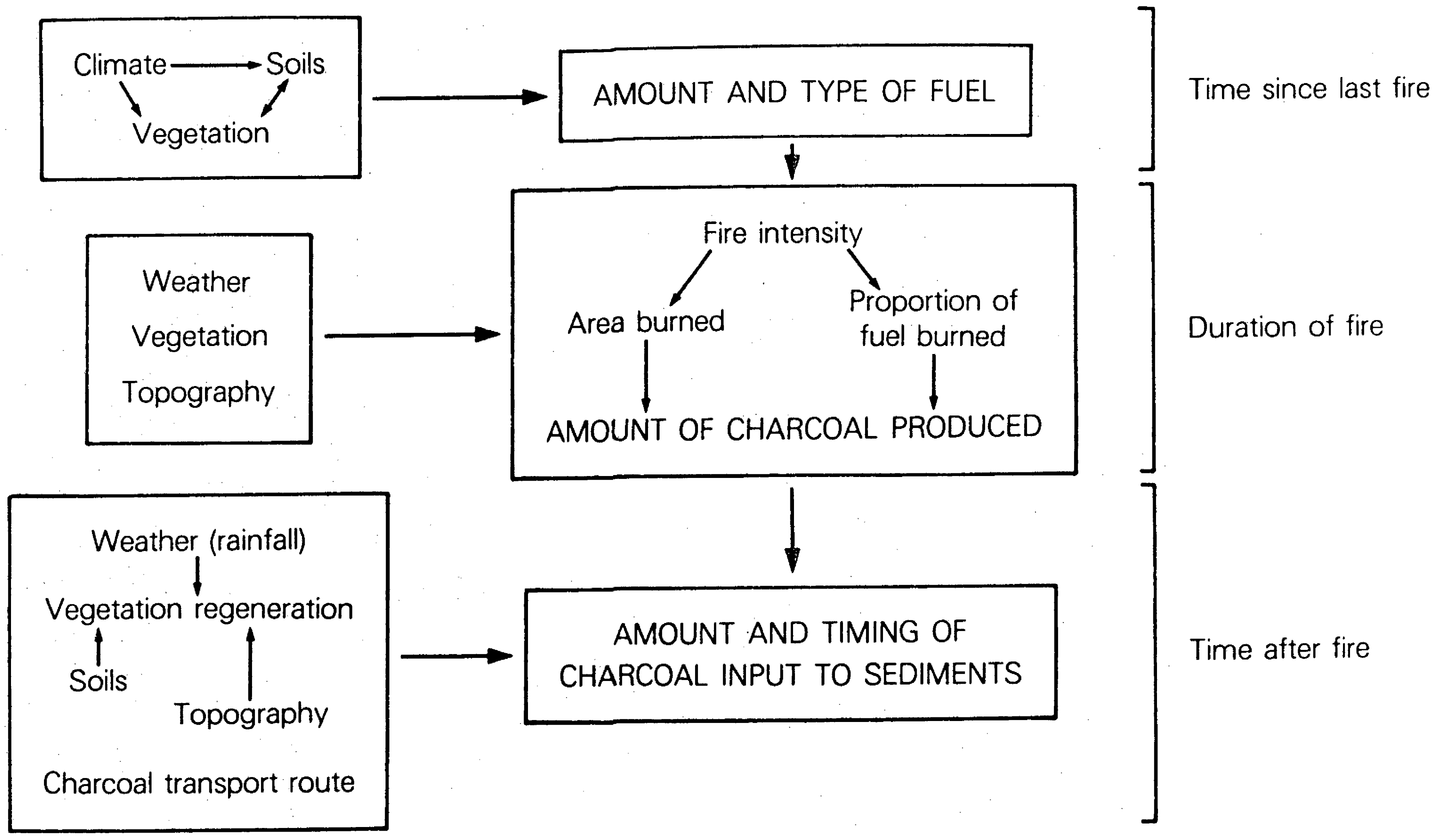


Figure 6.1. Major factors influencing the amount of charcoal deposited in sediments after a fire, and their interactions over time. All factors in the left-hand boxes, over the period indicated on the right and dependent on the amount of time, govern the outcome in the boxes in the centre. Arrows, within and outside boxes, show the direction in which factors influence each other.

the amount of charcoal deposited after each of a series of fires should indicate their relative magnitudes, in intensity or areal extent.

During a fire, charcoal may be transported in smoke or streams to deposition sites. Immediately after a fire, the amount and timing of charcoal deposition depends on the moisture content and water capacity of the soil, the duration and intensity of rainfall, the amount and structure of any remaining vegetation or litter, and the slope and roughness of the terrain. In the longer term, as vegetation regenerates and new litter accumulates, charcoal will be incorporated into the soil and litter, making it more difficult to move by surface runoff. If there is insufficient overland flow to carry charcoal into streams before the vegetation regenerates and a new litter layer is formed, very little charcoal might reach a deposition site. Thus, an extensive fire might be under-represented in, or missing entirely from, the sedimentary charcoal record.

The pattern of deposition in a sedimentary basin of charcoal from a fire is likely to be a series of pulses, with the first a small input of airborne fragments, augmented by charcoal falling into streams and washing into the lake. Subsequently, charcoal will be deposited with each rainfall event (cf. Chapter 5.3, 5.5), the amount depending on their frequency and intensity and the rates of regeneration of vegetation and accumulation of litter. The largest pulse of charcoal input will be from the first rainfall event, if it is of sufficient intensity, and the amount deposited subsequently will tend to decrease with time. This pattern will be made less distinct if the deposition site is some distance downstream from the burned area or if there is mixing of the sediments. Figure 6.2a presents the hypothetical input of charcoal to sediments over time, but the nature of the sediments and the sampling methods used will rarely allow the detailed input of charcoal by rainfall events to be discerned. The pattern of charcoal input could be generalized as a smoothed curve (Figure 6.2b).

Sediment sampling schemes and interpretation

When sedimentary sequences are sampled for pollen and other analyses, samples are usually taken at intervals of several centimetres. Depending on the rate of sedimentation, a number of years of deposition will be represented in each sample and there will be a gap of a greater number of years between samples. These two variables, the number of years within and between sediment samples, make up the sediment sampling scheme.

Charcoal input to sediments over long periods may be modelled using curves of input from individual fires, such as Figure 6.2b, and litter accumulation curves, such as Figure 6.3. Different sampling schemes can be applied to these input models and the resulting charcoal curves compared. In the simple model presented here, calculations have been based on the assumptions listed below. These assumptions only apply to the ideal situation, but are made here in order to show clearly the effects on results of changing the sampling scheme.

1. Annual input of charcoal from any one fire is inversely proportional to the square of the number of years since that fire. Short-term results from Bushrangers catchment (Chapter 5.5) suggest that this rate of decrease may be too rapid, but this does not affect the general argument that follows.

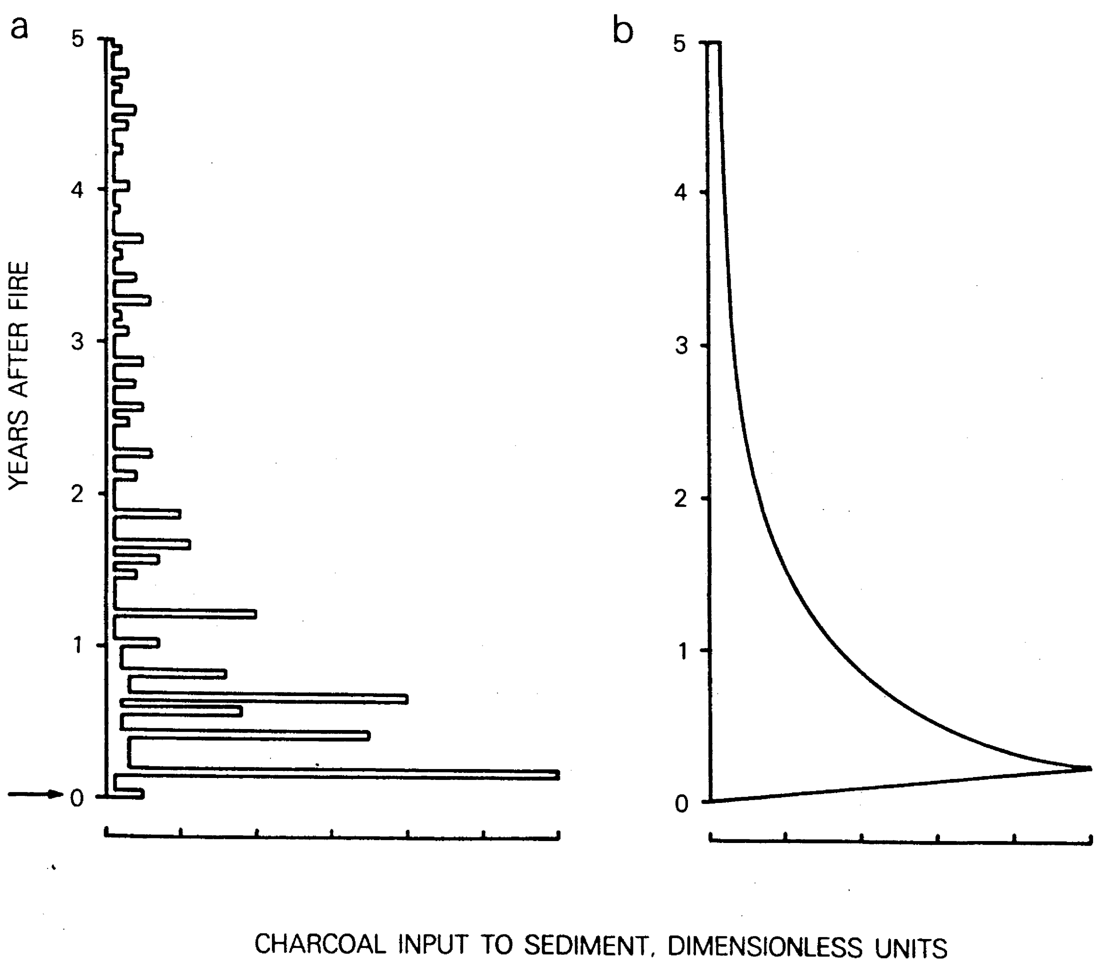


Figure 6.2. (a) Hypothetical input of charcoal to sediments over time after a fire. The initial pulse (arrowed) represents charcoal deposited from the air during a fire, while subsequent pulses are of charcoal transported by water in each rainfall event. (b) The same charcoal input represented by a smoothed curve.

2. Input of charcoal in the first year after a fire is directly proportional to the amount of fuel burned.

3. The amount of fuel burned is directly proportional to the amount of fuel present at the time of the fire, the area burned and the intensity of the fire.

4. The area burned and the intensity of a fire depend on the amount of fuel present at the time of the fire.

5. The amount of fuel present at the time of a fire is directly proportional to, or identical with, the amount of litter on the ground.

6. The amount of litter present at the time of a fire is proportional to the number of years since the last fire and may be calculated for any vegetation type from the formula:

$$F = (L/k)(1-\exp(-kt)),$$

where F is the amount of litter, L is annual litter production, k is the constant rate of decomposition of litter and t is the time in years since the last fire (Olson, 1963; J. Walker, 1979, 1981).

7. Rainfall is constant over time; that is, rainfall events of similar frequency and magnitude occur each year.

8. Annual increase in sediment thickness is constant and there is no compaction of sediments.

9. There is no vertical mixing of sediments.

For these calculations, two vegetation types with known rates of fuel accumulation were chosen: (a) mallee-broombush shrubland (_Eucalyptus incrassata_ and _Melaleuca uncinata_ association; Specht, 1966, cited by J. Walker, 1979, 1981); and (b) _Eucalyptus_ open forest (dry sclerophyll forest; Hutchings and Oswald, 1975, cited by J. Walker, 1979, 1981). Figure 6.3 shows fuel build-up over time in

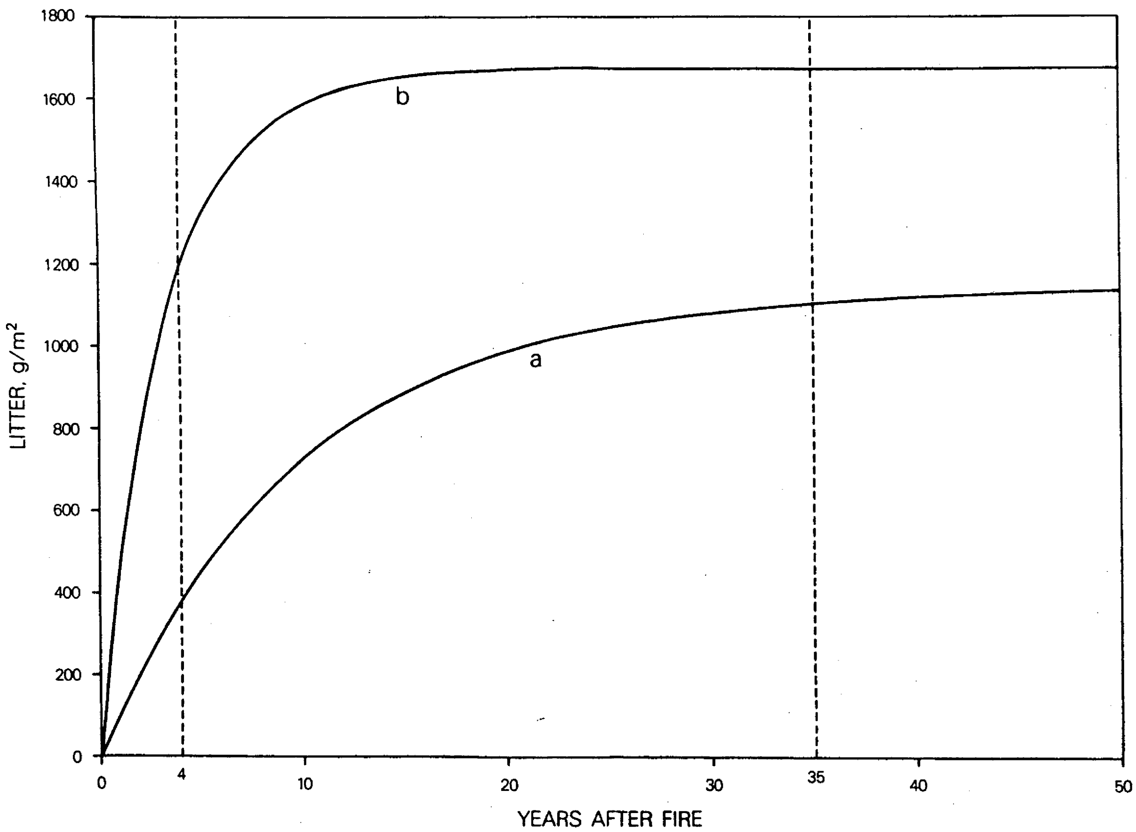


Figure 6.3. Litter accumulation over 50 years after a fire in two vegetation types: (a) mallee-broombush shrubland and (b) *Eucalyptus* open forest. Data from J. Walker (1979, 1981).

these two vegetation types, using the formula given above and values of L and k listed in Table 6.1. Two fire frequencies were selected, of 4 and 35 years, and it was assumed that fires at 35 year intervals burned 90% of the available fuel and those at 4 year intervals burned 50%. The latter correction also takes into account the smaller area likely to be burned by a less intense fire resulting from the lighter fuel load. Charcoal input to sediments in the first year after a fire was then calculated in dimensionless units as the proportion of the standing litter crop burned after 4 or 35 years. Table 6.1 summarizes these data and Figure 6.4 shows the theoretical annual charcoal input over 50 years for the selected vegetation types and fire frequencies.

Table 6.1. Estimation of charcoal input to sediments in the first year after a fire, in dimensionless units (C) proportional to the standing litter crop (F) at time (t) after the previous fire. L is annual litter production, k the decomposition constant and P the proportion of available fuel burned, in weight or area of ground. Estimates of L and k are from J. Walker (1979, 1981).

	L $g/m^2/y$	k	t y	F g/m^2	P	C
(a) Mallee-broombush shrubland	114	0.10	4	376	0.50	200
	"	"	35	1106	0.90	1000
(b) *Eucalyptus* open forest	502	0.30	4	1169	0.50	600
	"	"	35	1673	0.90	1500

If these fire frequencies remained constant for 5000 years and the sediments were sampled with 7 years in each sample and 110 years between samples, curves of charcoal content with time would appear as in Figure 6.5. If the sampling interval was changed to 200 years and the number of years in each sample to 20, the same data would appear as in Figure 6.6. From these diagrams, several points may be made:

1. In any vegetation type, different fire frequencies result in different curves of charcoal content over time. More frequent fires

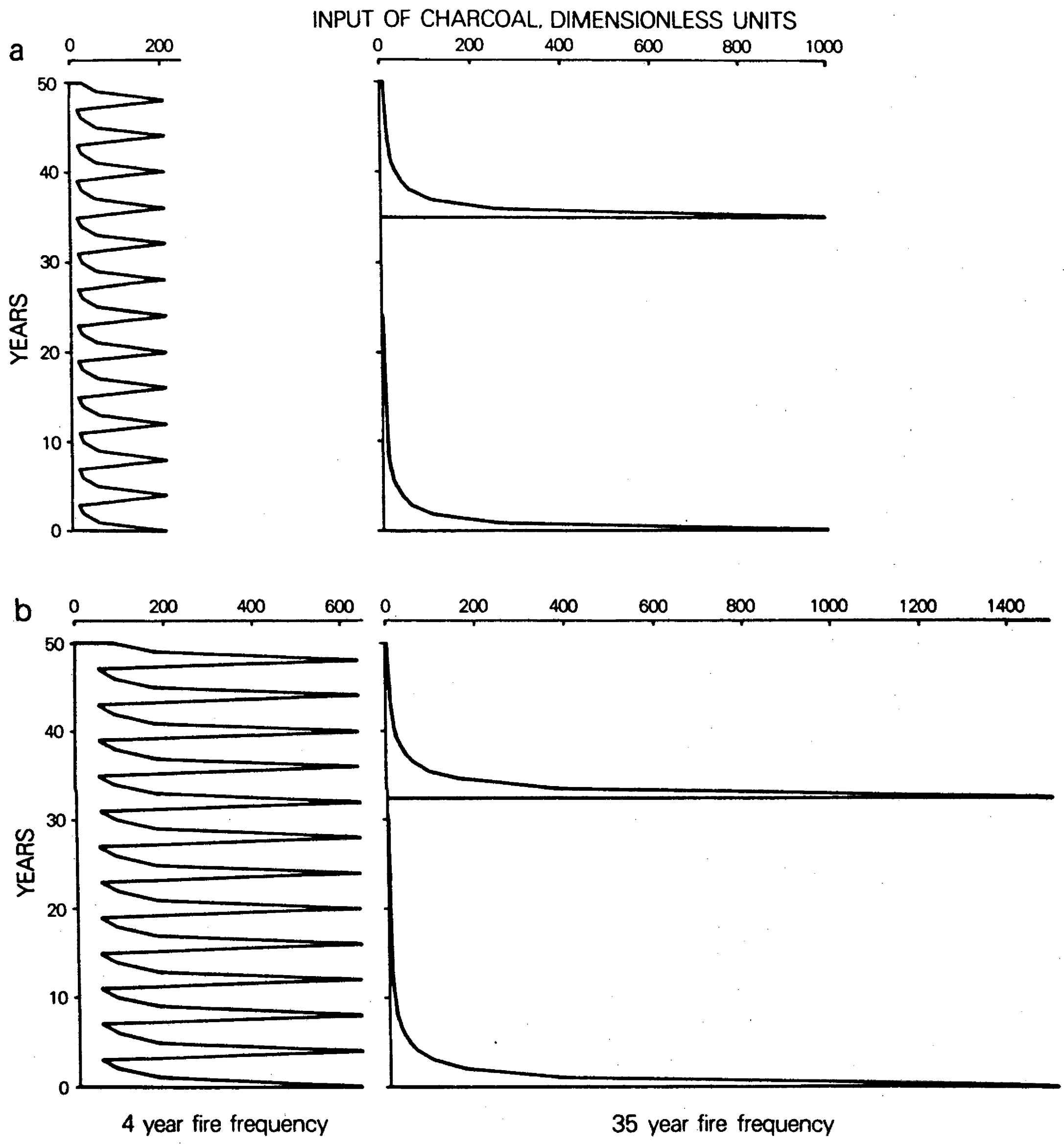


Figure 6.4. Theoretical approximations to annual charcoal input to sediments, in dimensionless units proportional to the standing litter crop, over 50 years in two vegetation types and with fire frequencies of 4 and 35 years. (a) Mallee-broombush shrubland, (b) *Eucalyptus* open forest. See text for details of calculations.

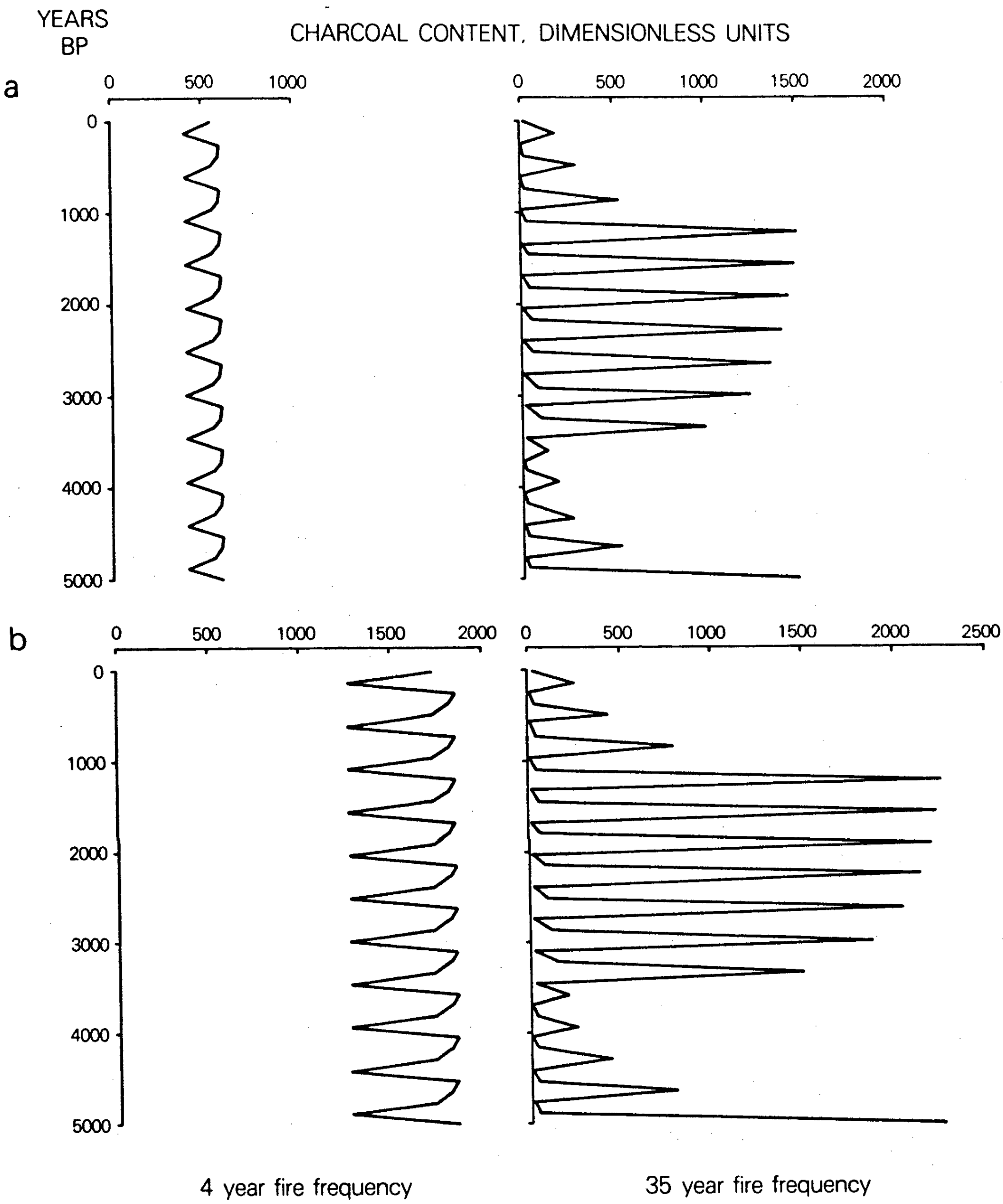


Figure 6.5. Curves of charcoal content resulting from sampling sediment with 7 years in each sample and 110 years between samples, assuming all environmental variables remained constant for 5000 years. Curves have been constructed using the data from Figure 6.4 for two vegetation types: (a) mallee-broombush shrubland and (b) *Eucalyptus* open forest, and fire frequencies of 4 years and 35 years.

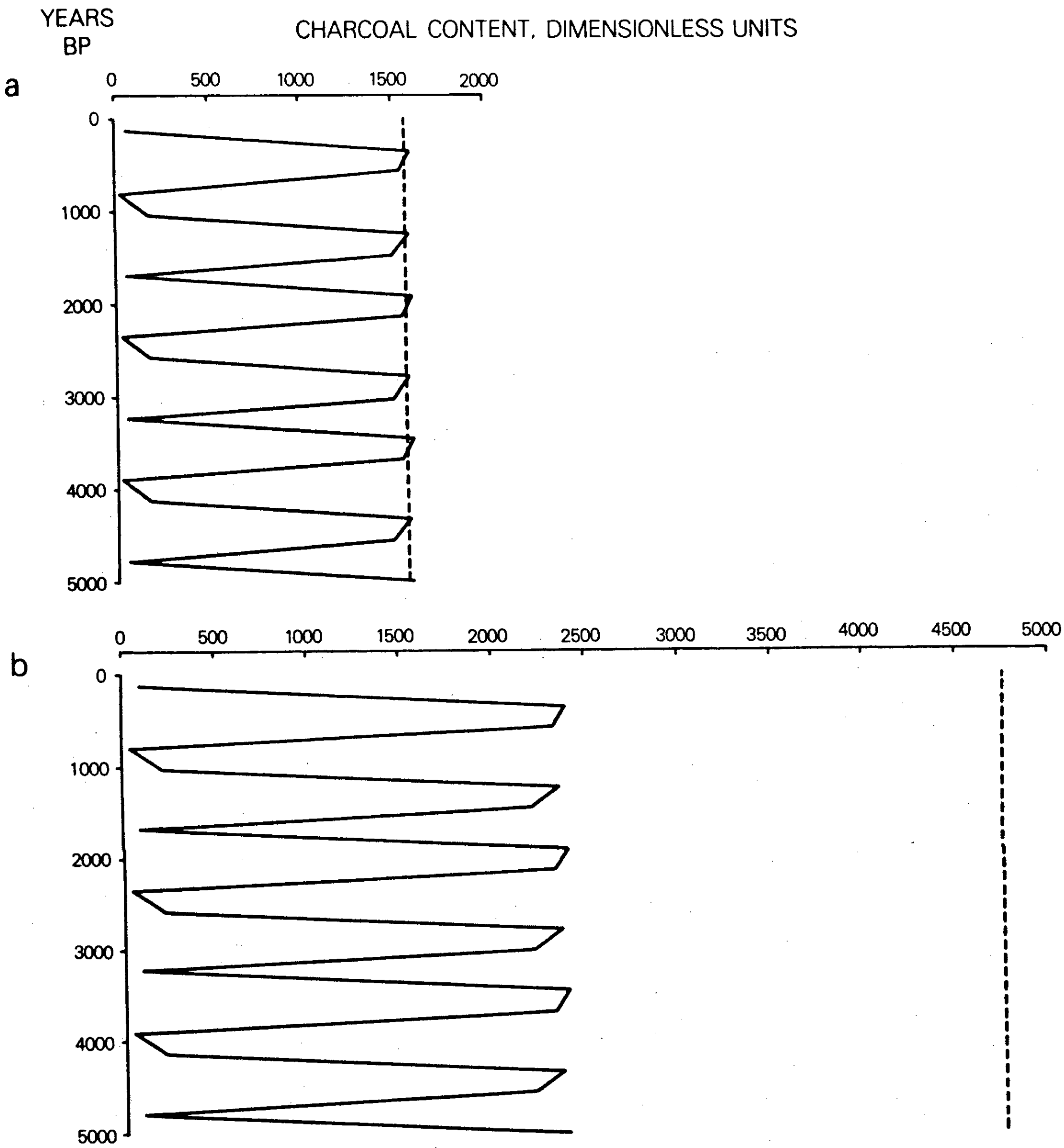


Figure 6.6. Curves of charcoal content resulting from sampling sediment with 20 years in each sample and 200 years between samples, assuming all environmental variables remained constant for 5000 years. Curves have been constructed using the data from Figure 6.4 for two vegetation types: (a) mallee-broombush shrubland and (b) *Eucalyptus* open forest, and two fire frequencies: 4 years (dashed lines) and 35 years (solid lines).

give a smoother curve and, with less frequent fires, there is a greater difference between maximum and minimum charcoal content.

2. A peak in a charcoal curve may represent one fire or several.

3. The amount of charcoal in any one sample may be independent of fire frequency, particularly where the rate of fuel build-up is high.

4. Changing the sampling scheme may radically alter the charcoal curve (compare Figures 6.5 and 6.6).

5. Individual fires or a sequence of fires might be missed altogether. A concrete example of this is provided in Figure 3.3, where the largest charcoal peak apparent in the detailed analysis is absent from, or reduced in importance in, the three charcoal curves constructed by sampling the basic data.

6. Depending on the sampling scheme, more charcoal in one series of samples than in another might result from more or less frequent fires. The common assumption that more charcoal indicates more frequent fires is not true in all cases.

7. Changes may appear in a charcoal curve that are artefacts of the sampling scheme and which would be wrongly interpreted as changes in fire regime. In the 35 year fire frequency curves of Figure 6.5 it appears that the fire regime between 3000 and 1000 years is quite different from that before and after.

The stability and regularity implied in this model are unrealistic, but useful for highlighting the necessity of taking the sediment sampling scheme into account when interpreting charcoal curves. Close sampling with as few years as possible in and between samples should be used if real changes in fire regime are to be distinguished from artefacts of the sampling scheme itself.

Conclusion

Reconstruction of fire history from sedimentary charcoal sequences is not straightforward, but errors in interpretation can be minimized by taking into account the problems of charcoal representation discussed in this chapter. Sometimes more than one interpretation might seem equally likely until further evidence is available. If a major change in fire regime appears in the initial charcoal analysis, close sampling across that boundary might remove any ambiguity in interpretation. In a few cases it might be possible to deduce the direction of change in fire regime from vegetation changes, if plant taxa known to be adapted to one fire regime are replaced by taxa known to be adapted to another. A useful distinction might be that between the smoother charcoal curves produced by higher fire frequencies and the greater fluctuations in those from lower fire frequencies (Figures 6.5 and 6.6). Further assistance might come from estimates of the likely rate of fuel build-up in a particular vegetation type with known or guessed climatic regime and soils. If the rate is high, then consistently high charcoal peaks might result from either more or less frequent fires, but if the rate is low, then less charcoal in one series of samples as compared with another probably indicates more frequent fires.

It cannot be assumed that all fires in the catchment of a lake are represented in the sedimentary record, nor that the relative magnitudes of charcoal peaks accurately reflect the amount of charcoal produced in fires. Apart from the effects of the sampling scheme, the year to year variation in rainfall, in its timing, intensity and magnitude, is important in determining the relative proportion of charcoal produced in different fires which is carried to the sediments. If there is little annual variation in rainfall, then smaller differences in charcoal quantities in sediments may be considered significant than if rainfall variation is high. Changes in a sedimentary basin, for example, from lake to swamp, will also lead to variation in charcoal representation as the source area will change.

It is often possible to assume that topography, soils and the charcoal transport route remain unchanged at any one site over a period of time. Vegetation and climate (both long- and short-term) will then be the primary determinants of changes in fire regime and of resultant changes in the amount of charcoal deposited in sediments (see Figure 6.1). With some knowledge of past vegetation and climate, deduced from the nature of the sediments and their biological inclusions, and taking account of factors affecting charcoal representation, it should be possible to outline past changes in fire regime from the sedimentary charcoal record.

Chapter 7

FIRE AND VEGETATION HISTORIES

To provide examples of the use of fossil charcoal to reconstruct fire history, pollen and charcoal in sediment from three contrasting sites in South Australia were analysed: (1) Lashmar's Lagoon, a coastal lagoon at the eastern end of Kangaroo Island (35°48'S, 138°04'E); (2) Black Creek swamp at Rocky River towards the western end of Kangaroo Island (35°57'S, 136°44'E); and (3) Little Swamp, a lagoon inland from Port Lincoln on the Eyre Peninsula (34°42'S, 135°47'E) (Figure 7.1).

Lashmar's Lagoon and Little Swamp occupy basins between Pleistocene calcarenites and older rocks, in the former case Cambrian metasandstones with a lateritised surface (Daily, *et al.*, 1979) and in the latter, Precambrian gneisses and schists (Parkin, 1969). Black Creek swamp is near a similar boundary, but fills a depression between a calcarenite dune and a low sandy ridge which separates the swamp from the flood plain of Rocky River.

The climate of the region is Mediterranean with most rainfall in winter. Mean annual rainfall and mean daily maximum and minimum temperatures for January and July are listed in Table 7.1. Winters are usually mild and summers warm, with temperatures a few degrees lower on Kangaroo Island than on the adjacent mainland. Prevailing winds are southeasterly in summer and northwesterly in winter (Laut, *et al.*, 1977; Burrows, 1979).

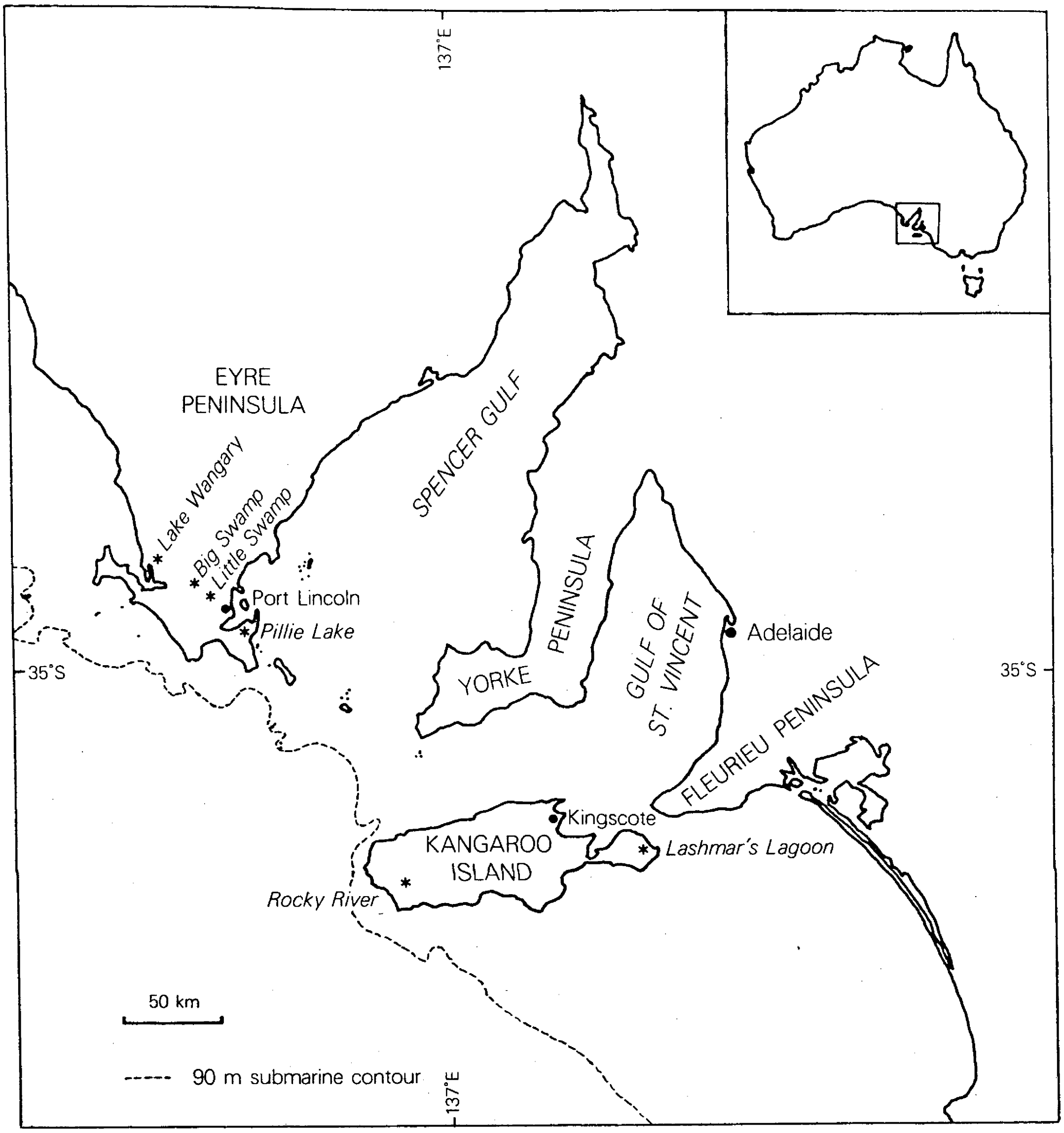


Figure 7.1. Map showing location of sites mentioned in Chapter 7.

Table 7.1. Approximate mean annual rainfall and maximum and minimum temperatures in January and July at three South Australian sites (from Laut, et al., 1977; Burrows, 1979).

	Lashmar's Lagoon	Rocky River	Little Swamp
Mean annual rainfall	550mm	800mm	470mm
Mean daily maximum temperature:			
January	21.4°C	22°C	25.5°C
July	14.1°C	14°C	15.9°C
Mean daily minimum temperature:			
January	15.5°C	14°C	15.9°C
July	9.6°C	9°C	8.4°C

At times of low sea level during the Quaternary, the Eyre, Yorke and Fleurieu Peninsulas and Kangaroo Island were connected by land. As sea level rose after the last glacial maximum, Kangaroo Island would have been separated before 9500 BP (Lampert, 1981) and Spencer Gulf flooded between then and about 6000 BP, when the sea reached its maximum Holocene level (Thom and Chappell, 1975; Burne, 1982).

Radiocarbon dates for Aboriginal occupation sites on Kangaroo Island range from about 16,000 BP to about 4300 BP (Lampert, 1979, 1981). Whether Aborigines occupied the island continuously, intermittently or very infrequently from the time it was cut off from the mainland is a matter for speculation (Jones, 1977), but it is clear from the accounts of Flinders and Péron, who were among the first Europeans to visit the island in 1802 and 1803, that it had then been uninhabited for some considerable time (Flinders, 1814; Péron and Freycinet, 1807-16). Aboriginal occupation of some antiquity on the Eyre Peninsula is suggested by Kartan tools found at several sites (Lampert, 1981). Occupation after the sea reached its present level is indicated by coastal sites (Lampert, 1981) and, in contrast to Kangaroo Island, Aborigines were present when Flinders explored the coastline in 1802 (Flinders, 1814).

The first Europeans to live in the area were sealers and whalers. Official settlements were founded at Kingscote on Kangaroo Island in 1836 and at Port Lincoln on the Eyre Peninsula in 1839. The land around Little Swamp was leased for farming in the 1840's, around Lashmar's Lagoon in the 1850's and at Rocky River in the 1890's. Most of the land at the three sites was cleared, burned, ploughed and grazed. Lashmar's Lagoon and Little Swamp remain surrounded by pasture, but in 1919 Rocky River station became part of a fauna and flora sanctuary which has since been declared a National Park.

The pre-European vegetation of Kangaroo Island was predominantly open woodland on the lateritic plateau that forms the main body of the island and open scrub on Pleistocene calcarenite, mainly along the south and west coasts. The dominant trees in both woodland and shrubland were species of Eucalyptus, those in the shrubland of mallee form with several stems arising from an underground lignotuber. The understorey and scrub were dense, species-rich and sclerophyllous, and composed mainly of Myrtaceae, Fabaceae, Casuarinaceae, Epacridaceae, Proteaceae, Asteraceae and Xanthorrhoea tateana (Liliaceae) (Specht, 1972; Clark, 1976; Lange, 1979). The density of the vegetation cover over most of the island and the lack of open grasslands hampered early European settlement (Clark, 1976).

Flinders described the southern Eyre Peninsula as barren, but with "a sufficient covering of grass, bushes and small trees not to look desolate" (Flinders, 1814, p.147), the trees being Casuarina and Eucalyptus (Flinders, 1814). Péron and Freycinet (1807-16) described the hills behind Port Lincoln as clothed with thick forests, but Péron had not seen the area, although Freycinet had. After the first

European settlers arrived in March, 1839, it was noted: "The greatest deficiency is in timber - nothing but the she-oak having been discovered within five miles of the coast" (letter to the South Australian Gazette and Colonial Register, 6 April, 1839, cited Baillie, 1978). Most of this Casuarina stricta (she-oak) woodland has since been cleared for grazing and cereal crops, but much of the mallee vegetation on dunes south of Little Swamp remains.

Cores of the top 4.5m of sediment from Lashmar's Lagoon (Clark, 1976) and of 1.4m of sediment from Little Swamp were taken with a Russian design D-section corer (Jowsey, 1966). A winch-operated rod-in-rod piston corer was used for the 2.5m Black Creek swamp sediments and, mounted on a raft, the full 12m of the Lashmar's Lagoon sediments. Further samples were taken directly from the wall of a trench excavated at the edge of Black Creek swamp (see Section 7.2). Cores were wrapped in plastic and later sampled in the laboratory. Sediment samples for pollen and charcoal analyses were $1cm^3$ in volume except those from the Black Creek swamp trench, where $2cm^3$ samples were taken from the upper six levels and $4cm^3$ samples from the lower two. Larger samples were necessary because pollen was sparse.

Samples for pollen and charcoal analyses from all three sites received the same basic series of processing steps (details in Chapter 2): hydrofluoric acid, sodium hydroxide, sieving, zinc bromide, acetolysis, dehydration and suspension in silicone oil. Samples from the earlier Lashmar's Lagoon core had been prepared similarly, but without the zinc bromide density separation of inorganics (Clark, 1976). All Lashmar's Lagoon samples were bleached with sodium chlorate and stained. The Little Swamp samples were first boiled for 30 minutes in 10% hydrochloric acid to remove carbonates and were also placed in an ultrasonic bath for 10 seconds, centrifuged at 1500rpm and the fine detritus decanted. Samples from the long Lashmar's Lagoon core and from Black Creek swamp were prepared before the effects of ultrasound on charcoal were discovered (Chapter 2), so no record was kept of whether the ultrasonic bath was used or not. To estimate pollen and charcoal concentrations, a tablet containing a known quantity of *Lycopodium* spores (Stockmarr, 1972) was added to each of the Lashmar's Lagoon samples, while concentrations in samples from the other two sites were estimated by using measured volumes at each sampling step.

Pollen was identified using the reference collection in the Department of Biogeography and Geomorphology at the Australian National University. Separation of *Casuarina stricta* pollen from that of other *Casuarina* species that occur, or may have occurred, in coastal South Australia, was made on the basis of size distributions of *Casuarina* pollen grains studied by Kershaw (1970). Pollen in each Lashmar's Lagoon sample was counted on transects across microscope slides until a total of at least 150 pollen grains from terrestrial plants other than Cyperaceae was reached. Little Swamp samples were counted until 100 terrestrial pollen grains other than *Casuarina* and Cyperaceae had been found; including *Casuarina*, the total number ranged from 161 to 336. Where possible, the Rocky river samples were counted to at least 150 terrestrial pollen grains other than Cyperaceae; where pollen was sparse, every pollen grain in each sample was counted. As the number of grains in each pollen sum was relatively small, the conclusions drawn from the pollen diagrams had to be conservative.

Because the point count method of estimating charcoal areas (Chapter 2.1) had not then been devised, charcoal particles in the Lashmar's Lagoon samples were counted and their concentrations and numbers relative to pollen grains calculated from the number of *Lycopodium* spores encountered. For samples from the first core (LL10), all charcoal particles with a maximum dimension greater than 25µm were included in the count (Clark, 1976); for samples from the long core (LL15), the minimum size was 19.5µm. The area of charcoal in samples from Little Swamp and Black Creek swamp was estimated by the point count method (Chapter 3.1). For the Little Swamp samples, counting continued until the relative standard deviation (s_p/P) was less than 20% and for the Black Creek swamp samples until s_p/P was less than 10% for most samples or less than 15% for those with little charcoal.

Results from each of the three sites are presented separately below and comparisons made in the concluding section of this chapter. Pollen diagrams include only the most abundant or indicator taxa; complete pollen counts are listed in Appendix B. Detailed descriptions of sites and present and past vegetation are not included as the aim here is simply to provide examples of the use of charcoal to reconstruct fire history.

7.1 Lashmar's Lagoon, Kangaroo Island

Lashmar's Lagoon is a shallow lake of about 0.5km^2 on the Chapman River at Antechamber Bay, Kangaroo Island. The river, which enters the lagoon at the south-west, and another small stream from the north-west, drain an area of about 60km^2. The lagoon overflows across a barrier 1.2m above sea level into the lower reaches of the Chapman River about 2km from its mouth, which is usually blocked by a beach berm. During floods the berm is breached and sea water can back up to the lagoon. This has been observed twice in the last fifty years (A. Lashmar, pers. comm.). Slopes surrounding the lagoon are pastured but some areas of mallee remain in the catchment. At the time of European settlement, the whole area was covered by dense mallee (Clark, 1976). Species of Ruppia and Chara are the dominant plants in the lagoon, with some Typha sp. and much Melaleuca halmaturorum growing at the margin.

Most of the sediments are dark grey organic clays and silts, but there is a layer of sand at the base and two phases of deposition of brown-grey silty clay with fibrous plant material (see Figure 7.2a). Five sections of the cores, which could be matched stratigraphically and by pollen content, have been dated by radiocarbon:

300- 320cm	2,440 ± 110 BP	(ANU-2171)	(Core LL15)
370- 390cm	2,750 ± 80 BP	(ANU-1775)	(Core LL10)
655- 673cm	4,720 ± 150 BP	(ANU-2172)	(Core LL15)
1160-1175cm	6,910 ± 370 BP	(ANU-1893)	(Core LL15)
1185-1201cm	10,060 ± 410 BP	(ANU-1872)	(Core LL15)

The lack of sediments from 10,000-7000 BP is probably because the sea first entered the lagoon basin at some time in that period; it was not until 7000 BP that conditions stabilized sufficiently for sediment to accumulate. A constant sedimentation rate is assumed in each of the four periods between known dates from 6910 BP to the present, so that dates within these periods, mentioned in the discussion which follows, are estimates only. The mean number of years for sediment to increase in thickness by one centimetre in each period was: 0-310cm, 7.9 years; 310-380cm, 5.2 years; 380-665cm, 6.9 years; and 665-1170cm, 4.4 years.

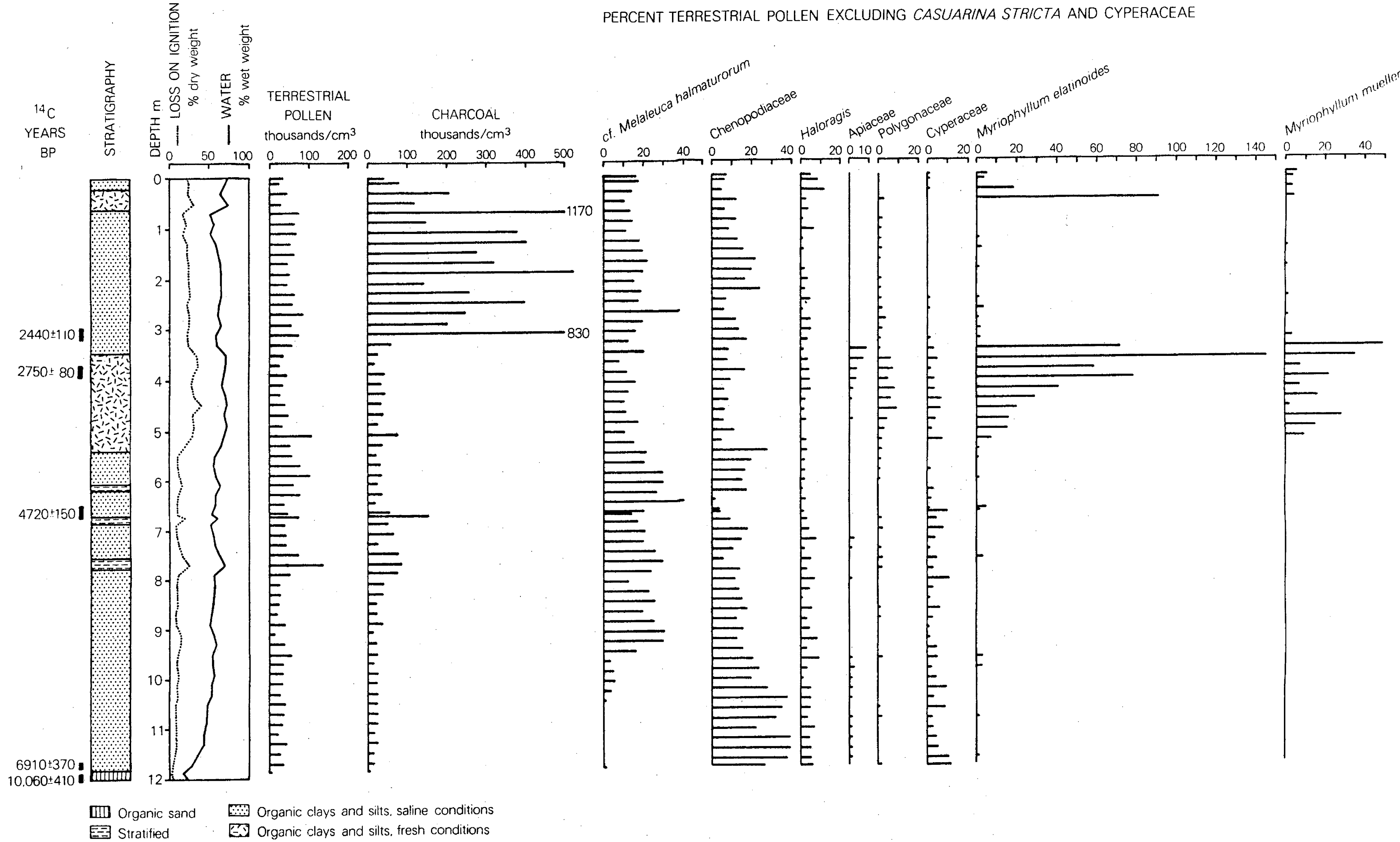
The lagoon has been under the influence of the sea for most of the time from 7000 BP to the present, except for two periods when the presence of large numbers of Myriophyllum pollen grains and Pediastrum coenobia indicate that the lagoon water was fresh. These are from about 3900 to 2700 years ago (541-347cm) and from about 400 to 150 years ago (65-18cm).

Results of analyses are summarized in Figure 7.2, which shows the stratigraphy, water content and loss on ignition of the sediments, ^{14}C dates, the relative abundances of selected pollen taxa and pollen and charcoal concentrations.

The vegetation from about 7000 to 6400 years ago (1175-1050cm) was more open than at any subsequent time till European clearing. During this phase Casuarina stricta increased in abundance while Chenopodiaceae, Asteraceae (Tubuliflorae) and Poaceae, with a few other shrubs, dominated in the understorey and probably covered large open areas. Once established, a Casuarina woodland persisted from about 6400 to 4800 years ago (1050-680cm), after which Eucalyptus replaced C.stricta as the dominant tree species and woody shrubs increased at the expense of grasses. This vegetation remained, with relatively minor fluctuations, from about 4800 to 1300 years ago (680-160cm). Asteraceae and shrub Casuarina species increased in abundance from about 1300 to 150 years ago (160-20cm). Europeans then arrived, increased the area of grassland, introduced alien species and virtually completed the destruction of Casuarina stricta in the area (20-0cm).

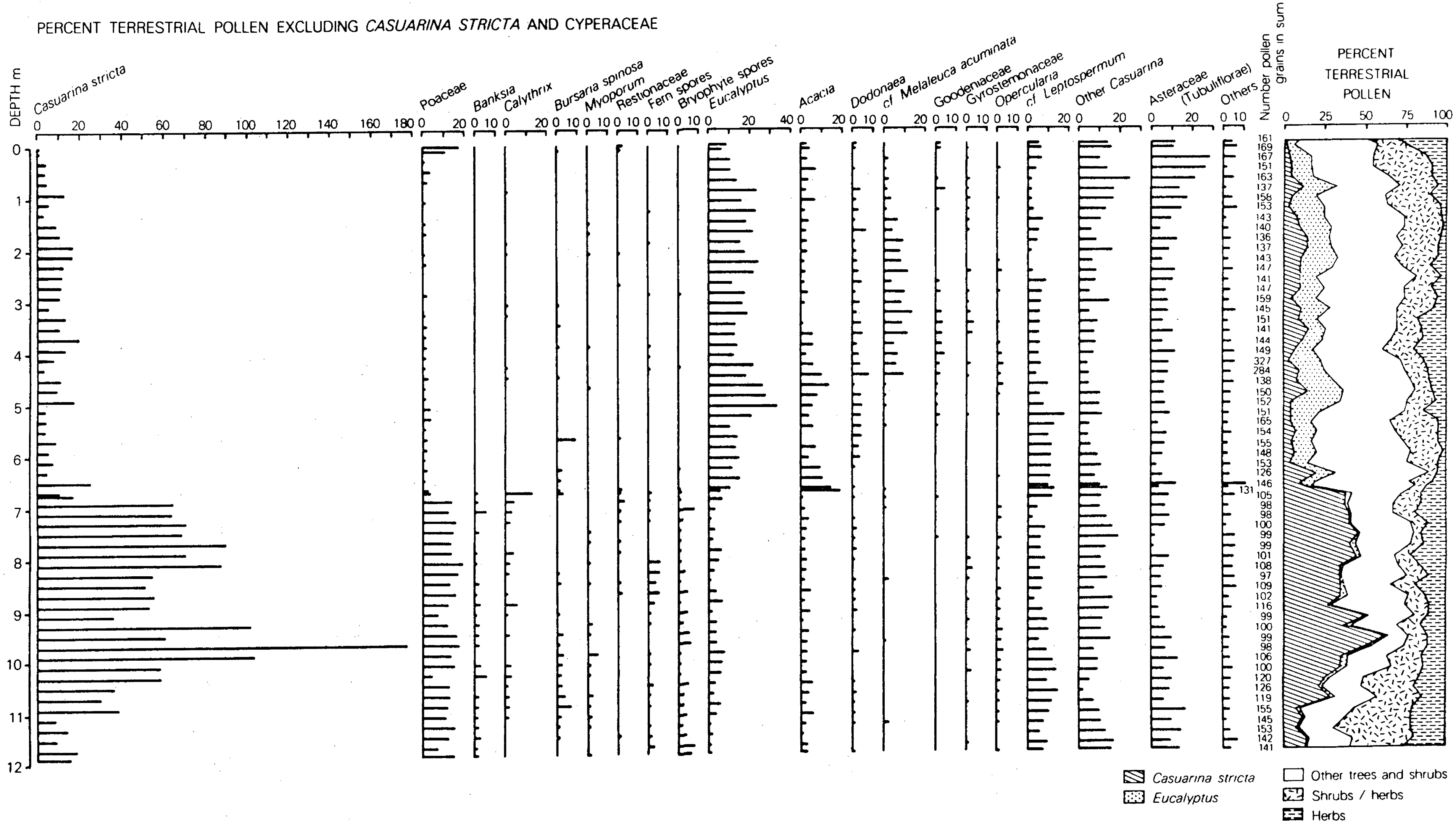
By comparing the curve of charcoal particle concentration in the sediments with that of pollen and with the amount of organic or inorganic matter (Figure 7.2a), changes in charcoal concentration that

Figure 7.2a. Pollen diagram from Lashmar's Lagoon, showing ^{14}C dates, sediment stratigraphy, loss on ignition and water content, pollen and charcoal concentrations and abundances of aquatic and probable wetland taxa expressed as percentages of total terrestrial pollen grains excluding Casuarina stricta and Cyperaceae. Results for the top 410cm are from core LL10 and for 470-1200cm from core LL15. Pollen spectra from the 430cm and 450cm samples from both cores (LL10 and LL15) were very similar and have been combined.



PERCENT TERRESTRIAL POLLEN EXCLUDING CASUARINA STRICTA AND CYPERACEAE
14C YEARS BP
STRATIGRAPHY
DEPTH m
LOSS ON IGNITION % dry weight
WATER % wet weight
TERRESTRIAL POLLEN thousands/cm3
CHARCOAL thousands/cm3
1170
830
cf. Melaleuca halmaturorum
Chenopodiaceae
Haloragis
Apiaceae
Polygonaceae
Cyperaceae
Myriophyllum elatinoides
Myriophyllum muelleri
2440±110
2750± 80
4720±150
6910±370
10,060±410
Organic sand
Stratified
Organic clays and silts, saline conditions
Organic clays and silts, fresh conditions

Figure 7.2b. Pollen diagram from Lashmar's Lagoon (continued), showing abundances of dry land taxa and fern and bryophyte spores expressed as percentages of total terrestrial pollen grains excluding *Casuarina stricta* and Cyperaceae. Also included are the number of grains in each pollen sum and a summary diagram including all terrestrial pollen taxa. Results for the top 410cm are from core LL10 and for 470-1200cm from core LL15. Pollen spectra from the 430cm and 450cm samples from both cores (LL10 and LL15) were very similar and have been combined.


PERCENT TERRESTRIAL POLLEN EXCLUDING CASUARINA STRICTA AND CYPERACEAE
DEPTH m
Casuarina stricta
Poaceae
Banksia
Calythrix
Bursaria spinosa
Myoporum
Restionaceae
Fern spores
Bryophyte spores
Eucalyptus
Acacia
Dodonaea
cf Melaleuca acuminata
Goodeniaceae
Gyrostemonaceae
Opercularia
cf Leptospermum
Other Casuarina
Asteraceae (Tubuliflorae)
Others
Number pollen grains in sum
PERCENT TERRESTRIAL POLLEN
Casuarina stricta
Eucalyptus
Other trees and shrubs
Shrubs / herbs
Herbs

are independent of changes in sedimentation conditions may be identified. The increase in charcoal between about 5300 and 4800 years ago (800-670cm) suggests that there were either more frequent or more intense fires at that time. But this increase was relatively minor compared to that which occurred about 2500 years ago (310cm), a change that was sustained until the arrival of Europeans, when charcoal particle numbers fell again (10cm).

From the relative abundance below 680cm of Cyperaceae pollen and spores from ferns and bryophytes, it is suggested that the climate prior to about 4800 BP was marginally wetter than today. After that time, the climate probably became drier, as fern and bryophyte spores are rare and Cyperaceae pollen is infrequent except during periods when the lagoon water was fresh. This climatic change is probably sufficient to explain both the major vegetation change around Lashmar's Lagoon about 4800 years ago and the increase in charcoal in the sediments, as the onset of drier conditions could have led to more intense fires which in turn may have facilitated the replacement of *Casuarina stricta* woodland by eucalypts and woody shrubs.

One of the vegetation types used as an example in Chapter 6 was a mallee-broombush shrubland, probably very similar to the vegetation around Lashmar's Lagoon over the last 5000 years. Figure 6.4(a) shows the very different patterns of charcoal input to sediments to be expected if this vegetation type burned at frequencies of 4 years or 35 years. If these fire frequencies remained constant and sediment was sampled with similar numbers of years within and between samples as were used to sample the Lashmar's Lagoon sediments, the resulting curves of charcoal concentration would appear as in Figure 6.5(a). The lower part of the Lashmar's Lagoon charcoal concentration curve

(1200-315cm) is similar to the pattern expected from a high fire frequency and the upper part of the curve (310-30cm) with that expected from a lower fire frequency. The greater amounts of charcoal particles and the large fluctuations in those amounts after about 2500 BP is consistent with a pattern of intermittent high intensity fires with considerable accumulation of litter between them. Until this time, the relatively small amounts of charcoal particles and the lesser fluctuations suggest a pattern of more frequent burning by low intensity fires with less litter accumulation between fires. After the arrival of Europeans, who used fire frequently and deliberately, charcoal concentration decreased.

The physical and chemical properties of the sediments, and the molluscs and algae they contain (Clark, 1976), suggest there was no significant change in climate or in sedimentation conditions corresponding with the change in fire regime about 2500 BP. It is thus likely that Aborigines were present and using fire regularly around Lashmar's Lagoon from before 7000 BP until about 2500 BP. That charcoal quantities remained low when a more flammable vegetation type became established in a drier climate about 4800 BP supports this contention. The marked change in fire regime about 2500 BP had little or no long-term effect on the vegetation; perhaps this is to be expected in vegetation composed of species well adapted to survive fires.

Could the postulated change in fire regime be simply an artefact of sample preparation? Samples from the earlier 4.5m core were processed without zinc bromide density separation of inorganics used for samples from the 12m core. It was shown in Chapter 2 that this step considerably reduces the number of charcoal particles. Some correction for this effect results from the use of 25μm as the minimum length of charcoal particles included in the counts of samples from the 4.5m core and 19.5μm as the minimum length for samples from the 12m core. Charcoal concentrations in samples from overlapping sections of the cores are shown in Figure 8.7b, but although these suggest that some charcoal was lost in the density separation, the change in concentration and, hence, fire regime at 310cm is evident in both cores.

7.2 Black Creek swamp, Rocky River, Kangaroo Island

Black Creek swamp is about 1.4km long and up to 0.3km wide, with a catchment area of about 9km^2 to the east of the swamp. The swamp drains into a karst depression at its western end which is about 60cm lower than the coring site. An overflow, 35cm higher than the depression, leads to Rocky River, about 1.5km downstream. The swamp is about 60m above sea level.

The main interest of Black Creek swamp is a deposit of fossil bones and teeth, including those of the extinct giant marsupials *Diprotodon*, *Zygomaturus* and *Sthenurus*, at the southern margin of the swamp. These were discovered in 1907 and first excavated in the 1930's by Tindale and others (1935). In the 1970's, J.H. Hope made new excavations and re-examined the material collected earlier (J.H. Hope, *et al*., in prep.).

To find the extent of the bone bed and its relationship with the stratigraphy of the swamp, the area was surveyed and augered. Samples for pollen analysis were taken from a trench excavated in the bone bed and from a core from the deepest part of the swamp near the excavation. It was hoped that some reconstruction could be made of the environment in which the extinct megafauna lived and died.

The vegetation around Black Creek swamp is similar to that at Lashmar's Lagoon before clearing, with mallee scrub on calcarenite dunes, but there are some floristic differences. The western end of the swamp, which was relatively undisturbed by agriculture, has a dense cover of Gahnia trifida and Melaleuca gibbosa with scattered Acacia spp., Xanthorrhea tateana and other shrubs. Downstream along Black Creek there is a dense thicket of Leptospermum juniperinum. Inhabitants say that the swamp is drier now than it was forty years ago (G. Lonzar, pers. comm.).

The stratigraphy of the swamp is complex, with many layers lensing out over a few metres. The bone bed is separated from the main swamp by a cemented silt ridge and there is no direct connection between the organic matrix of the bones and the swamp sediments. Small fragments of bone were found near the base of two auger holes in the centre of the swamp. If these bones had been washed in from the swamp edge, then the swamp deposits mostly post-date the bone-bed. The stratigraphy of the swamp core and the part of the trench which was sampled are shown in Figure 7.3. Sharp boundaries between some sediment layers suggest that sedimentation has not been continuous, while mottling and incorporation of clay and lateritised pellets indicate some oxidation and reworking of older sediments from upstream or around the swamp. Hard peat pellets in the matrix around the bones were not found in the main swamp.

Several radiocarbon age estimations have been made of material from the bone bed and from the pollen core. Two fractions of the matrix surrounding bones in the organic silts of an earlier (1974) excavation gave ages of 19,000$\pm$310 BP (ANU-1681A) and 18,600$\pm$300 BP

(ANU-1681B). An anomalous date of 4260±90 years BP (ANU-1960) was obtained from organic material separated by flotation from grey silts underneath the cemented layer of the silt ridge which separates the bone bed from the main swamp. It was expected that this ridge would pre-date the bone bed, thus providing a maximum age for the bones, with the matrix dates being the minimum age. The date obtained suggests contamination by more recent material from above. If the minimum age of 19,000 years applies to the bones as well as their matrix, then this site, along with Spring Creek in Victoria (Flannery and Gott, in press), records the most recent survival of an assemblage of megafauna in Australia, although bones from single species have been found in younger contexts (J.H. Hope, et al., 1977; Murray, et al., 1980).

Four radiocarbon dates have been obtained from sections of the pollen core (Figure 7.3). These are:

70- 80cm	1,960 ± 120 BP (ANU-2170)
130-140cm	16,000 ± 200 BP (ANU-2768)
170-180cm	15,040 ± 120 BP (ANU-2767)
180-190cm	16,900 ± 390 BP (ANU-1961)

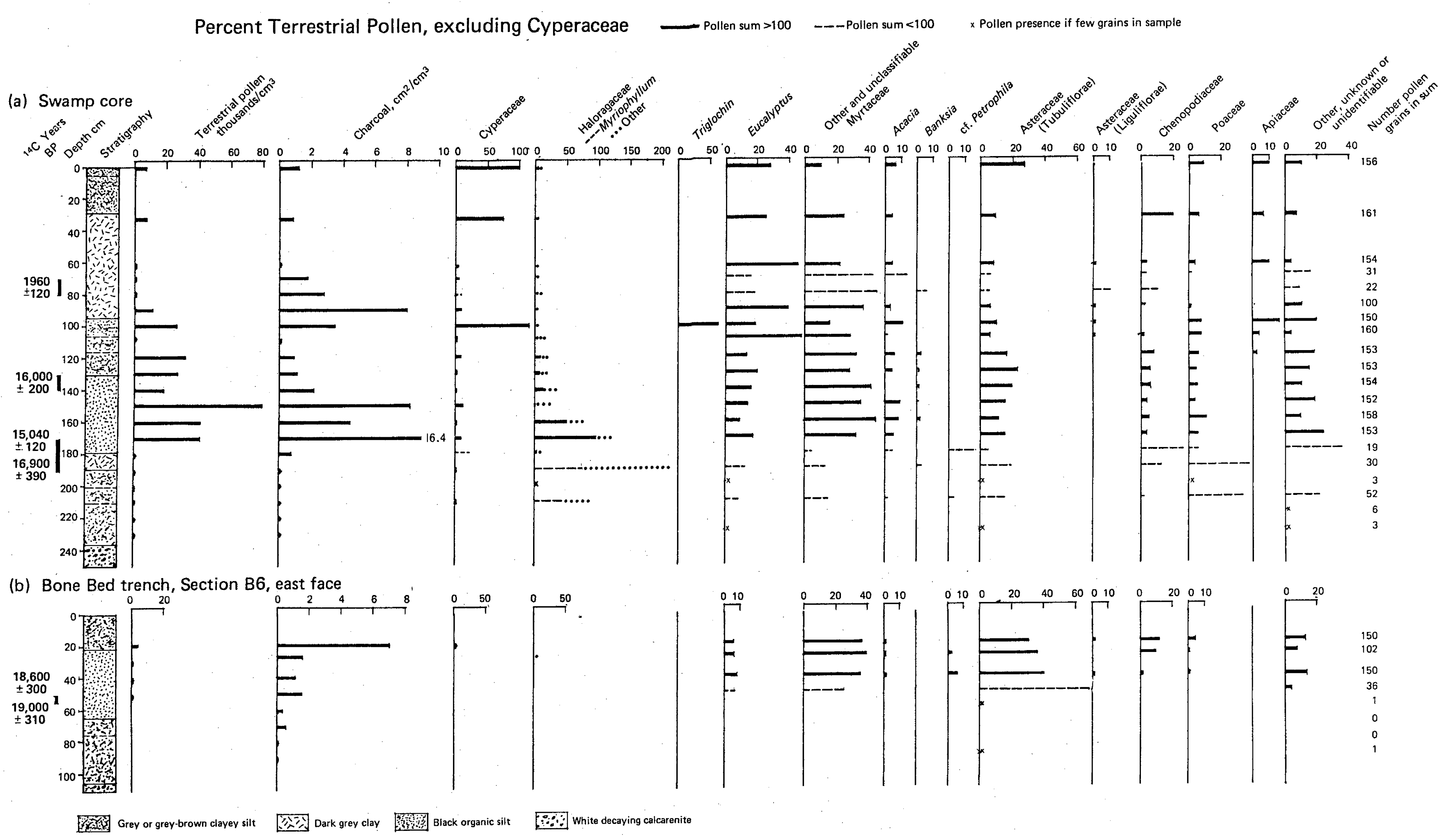
As suspected, most of the swamp sediments post-date the emplacement of the bones. It is also evident that deposition rates have varied greatly and that there are gaps in the record, most noticeably between 16,000 BP and 2000 BP. Although the lowest three dates are not sequential and the 95% confidence limits of ANU-2768 and ANU-1961 overlap, it is most likely that these sediments are of late Pleistocene age, rather than early Holocene. Redeposition of older material may have contaminated sample ANU-2768. The sediments are likely to reflect not only changes in runoff from the Black Creek catchment, but also changes over time in the relationships between Black Creek, Rocky River and the Rocky River flood plain, and the construction or removal of barriers between these. For example, deposition in the swamp may have begun because of a change in the course of or damming of Black Creek rather than being due to increased precipitation.

Pollen was badly preserved in most of the samples and sometimes difficult or impossible to identify. The pollen taxa represented are generally thick-walled and resistant to breakdown, while each taxon includes ecologically diverse species. Thus, little can be deduced about details of past vegetation, but the relative abundances of the predominant and most resistant pollen types probably reflect relative abundances in the vegetation of the past, rather than differential preservation.

Results are summarized in the pollen diagram in Figure 7.3. Pollen abundances are expressed as percentages of the total number of terrestrial pollen grains other than Cyperaceae counted at each level. The number in each pollen sum is included on the diagram and, where less than 100 terrestrial pollen grains have been counted, percentages are indicated by dashed lines. Where there were very few pollen grains, the presence of a taxon is indicated by a cross. Only two pollen grains, both Asteraceae (Tubuliflorae), were found in the lowest four samples from the trench and very few in the lowest levels of the core. Also shown in the diagram are estimates of the number of terrestrial pollen grains and of the area of charcoal per cubic centimetre of sediment.

Both pollen and charcoal are sparse in the clays, clayey silts and marls of the bottom section of the swamp core (samples 230-180cm). <u>Myriophyllum</u> pollen indicates that throughout this time there was open and flowing water for sufficiently long periods for the establishment

Figure 7.3. Pollen diagram from Black Creek swamp, Rocky River, showing ^{14}C dates, sediment stratigraphy, pollen and charcoal concentrations, abundances of terrestrial and aquatic taxa expressed as percentages of total terrestrial pollen other than Cyperaceae, and the number of terrestrial pollen grains counted in each sample. Percentages of less than 100 pollen grains are indicated by dashed lines; crosses show the presence of a taxon in samples containing very few pollen grains. Because of poor pollen preservation it was often difficult to attribute Myrtaceae pollen grains to a genus or group of genera and to separate *Myriophyllum* from *Haloragis* in the Haloragaceae.
(a) Swamp core samples. (b) Bone bed trench samples.


Percent Terrestrial Pollen, excluding Cyperaceae
Pollen sum >100
Pollen sum <100
x Pollen presence if few grains in sample
(a) Swamp core
^{14}C Years BP
Depth cm
Stratigraphy
Terrestrial pollen thousands/cm3
Charcoal, cm2/cm3
Cyperaceae
Haloragaceae
Myriophyllum
Other
Triglochin
Eucalyptus
Other and unclassifiable Myrtaceae
Acacia
Banksia
cf. Petrophila
Asteraceae (Tubuliflorae)
Asteraceae (Liguliflorae)
Chenopodiaceae
Poaceae
Apiaceae
Other, unknown or unidentifiable
Number pollen grains in sum
1960 ±120
16,000 ± 200
15,040 ± 120
16,900 ± 390
16.4
(b) Bone Bed trench, Section B6, east face
18,600 ± 300
19,000 ± 310
Grey or grey-brown clayey silt
Dark grey clay
Black organic silt
White decaying calcarenite

and maintenance of aquatic vegetation. The paucity of Myriophyllum pollen at 180cm in the core may reflect drier conditions around the height of the last glacial rather than bad preservation, as it is comparatively abundant at 190cm and 210cm, where terrestrial pollen is scarce. The high proportion of grass pollen in the 210cm and 190cm swamp core samples suggests that the vegetation before about 17,000 BP was more open than at any time since. While pollen numbers are very small in these samples, there is no reason to expect grass pollen to be better preserved than that from Eucalyptus or other Myrtaceae, so that predominance of grass pollen probably does reflect the surrounding vegetation.

By 15,000 BP, the swamp was most productive, probably with much open water, as indicated by organic detritus in the sediment and Myriophyllum pollen (170-130cm). Eucalyptus and Myrtaceous shrubs, such as Melaleuca and Leptospermum, increased in abundance around and possibly within the swamp. The abundance of Myriophyllum pollen decreases from 170cm to 106cm and its disappearance corresponds with a change from organic-rich detritus to clayey silts, which suggests less stable conditions.

As the swamp surface became drier (106-63cm), eucalypts increased relative to shrubs and herbs. Pollen from Asteraceae (Liguliflorae, probably Microseris), and from a species of Apiaceae, appear for the first time. These are both likely to be herbs growing very near the core site. There was a unique phase, of unknown duration (100cm), of marshy vegetation, with Cyperaceae and Triglochin dominant. At this level there are also fewer Myrtaceae pollen grains, particularly Eucalyptus, than in adjacent samples.

Some time within the past two thousand years the swamp became wetter again and the present vegetation was established (33-0cm). The top two samples are very similar, except for the large percentages of chenopod pollen at 33cm and of Tubuliflorae pollen at the surface. The latter may well come from introduced weeds.

Pollen is virtually absent from the lower levels of the trench and sparse in the upper levels. The absence of Myriophyllum pollen, compared with its preservation in the lower levels of the swamp core, suggests that open water did not extend over the bone bed. None of the trench pollen spectra can be matched with the swamp core spectra, mainly because of the high proportions of Asteraceae pollen in the former. On the other hand, the four pollen-containing samples from the trench are very similar to each other, suggesting that either the pollen there was incorporated over a relatively short period and there has been little deposition since, or the local vegetation remained little changed over a long period, or there has been considerable mixing of the black organic silts in which the pollen is incorporated. Small Leptospermum or Micromyrtus pollen grains in the top two samples (18-20cm and 25cm) are not found in the 40cm sample and this, along with larger numbers of chenopod pollen grains, suggests that mixing has not taken place. The small Leptospermum grains are most abundant in the swamp core between 160cm and 33cm. Pollen attributed to Petrophila appears in the trench samples as well as in the lowermost part of the swamp core, while Banksia pollen is present in the core but absent from the trench. Most notable is the dearth of grass pollen in the trench samples. This is consistent with the bone bed pre-dating the open grassy period recorded early in the swamp core, but the pollen preserved in the trench might have been of predominantly local origin, with the bone bed occupying a relatively dry bank at the edge of a swamp or lake.

Charcoal concentrations in the samples contain more information about sedimentation or preservation conditions than about fire history. At most levels of the swamp core there is a good correlation between pollen and charcoal concentrations. Where both pollen and charcoal are sparse, they were either originally sparse in the sediments or have been destroyed since. When the swamp was open water, conditions were best for charcoal deposition and preservation, there could have been more charcoal washed into the swamp from a larger catchment area, or there may have been more charcoal produced from larger amounts of fuel available in the wetter climate (Chapter 6). When the swamp dried, most charcoal would have come from fires burning across the swamp surface (Chapter 4). The comparatively large quantities of charcoal from 100cm to 70cm, along with a visible charcoal band at 77cm, suggest that the swamp surface might have burned during that period.

The trench samples all contain charcoal, probably produced by local fires. As the length of time of deposition is not known, nothing can be said about relative frequencies of these fires. The large quantity of charcoal in the uppermost sample could be from European burning as it is from a layer which has probably been ploughed.

The open grassy vegetation at Rocky River around the height of the last glacial (ca. 20,000-18,000 BP) is similar to that recorded from other sites in southeastern Australia for that time (G.S. Hope, 1978 and in press) and is consistent with the openness of vegetation deduced from the fauna preserved in the Seton rock shelter on Kangaroo Island (J.H. Hope, _et al_., 1977). Bowler (1978) provides evidence from aeolian dune formation for aridity at the eastern end of Kangaroo Island at the height of the last glacial. The abundance of water at Rocky River suggested by Myriophyllum pollen apparently conflicts with this evidence, but problems with stratigraphy, dating and pollen preservation at Rocky River make the evidence from there equivocal. The edge of the continental shelf is close to the western end of Kangaroo Island, so the proximity of Rocky River to the sea at a time of minimum sea level (Bowler, 1978) may have resulted in higher effective precipitation than on the east of the island, which then formed part of the mainland.

Disjunctions in the sediments of the Black Creek swamp core and the lack of adequate dating do not allow a detailed reconstruction of Holocene environments. There is no obvious equivalent to the early Holocene wet phase recorded at Lashmar's Lagoon (Section 7.1) and at other sites in southeastern Australia (Bowler, et al., 1976). The drier period above 94cm in the Black Creek swamp core, ending some time after 2000 BP, may be equivalent to that recorded between about 5000 and 1500 BP at Lashmar's Lagoon (Figure 7.2) and other Holocene sites (Bowler, et al., 1976). No Casuarina pollen was found at Rocky River, in stark contrast to its abundance at Lashmar's Lagoon, particularly before 5000 years ago. Eucalypts and Myrtaceous shrubs appear to have dominated the vegetation at Rocky River from about 15,000 years ago until the present day, but several thousand years of the record of this period may be missing from the sediments. The establishment of this vegetation soon after the height of the last glacial suggests that the western end of Kangaroo Island may well have acted as a forest refugium through a period of adverse climatic conditions elsewhere.

7.3 Little Swamp, Eyre Peninsula

Little Swamp is a shallow lake, about 70m above sea level, completely surrounded by pasture, but with several old *Eucalyptus camaldulensis* trees at its margin. It has an area of about $2km^2$ and a catchment of about $100km^2$; two intermittent streams enter the swamp from the north, and it overflows along Duck Ponds Creek to the south. The name, Little Swamp, suggests that it might have been covered by reeds at the time of European settlement, but it has been a shallow lagoon for a considerable time, drying frequently. The sediment surface is flat with an almost continuous vegetation cover, mainly of *Chara* sp. and *Ruppia* sp.

Little Swamp was selected as a site on part of the mainland, close to Kangaroo Island, that had probably been inhabited by Aborigines during the Holocene. Pollen and charcoal analyses were aimed only at discovering whether there were changes in vegetation or fire regime corresponding with those at Lashmar's Lagoon, so a minimum number of samples was analysed.

Three cores of up to 139cm of sediment taken at different locations in the lagoon had similar stratigraphy, with black organic silts above about 80cm and, below that, alternate layers of grey or white calcareous clay and brown organic detritus. Detailed stratigraphy of the core used for analysis is given in Figure 7.4. Either the base of the sediments was at about 150cm or compaction of sediments prevented deeper penetration with a manual corer. One radiocarbon age estimation of 6410 ± 100 BP (ANU-2511) was made on organic sediments from 117-128cm of the core.

Four sediment cores were taken from nearby Big Swamp (Figure 7.1) which showed similar stratigraphy to Little Swamp. The radiocarbon age of sediment from 72-90cm of one of these cores was 5130±220 BP (ANU-2510), which confirms the date from lower in the Little Swamp sediments. Coring was also attempted in Lake Wangary (Figure 7.1), but the compacted, laminated clays of its sediments prevented more than 94cm being obtained with a D-section corer.

The stratigraphy of the Little Swamp sediments suggests fluctuations in lake conditions below 75.5cm, with phases of abundant growth of aquatic plants alternating with periods of deposition of calcareous material. Above 75.5cm, more stable conditions are indicated by relatively homogeneous sediments of black organic detritus with calcareous silts. The coarser and less organic sediments of the top 20cm are probably post-European or reflect European disturbance. The small amount of sediment (ca. 125cm) deposited over 6500 years may result from a slow sedimentation rate, from gaps in the record, or both.

Ostracods in the sediments have been investigated by P. De Deckker (pers. comm.) to provide the following information on past water conditions (De Deckker, 1981a, b and c). When the basal organic layer (139-133.5cm) was deposited the water in the swamp was fresh; since then it has been slightly saline with occasional short fresh periods. The five light-coloured calcareous clay layers of the lower part of the core (139-78cm) were deposited in periods of higher water level than in the intervening times of organic deposition. Organic deposits from 75.5cm to 20cm were laid down at a time of very low water level. The two periods when organic clays and shells were deposited (78-75.5cm and 20-11cm) were similar and the water had a maximum salinity of 3ppt. Water was more saline (up to 6ppt) in the most recent period (11-0cm). Only in this uppermost section are charophyte remains calcareous, indicating acid conditions below.

Changes in the sediments of Little Swamp have some similarities with those at Pillie Lake, a saline lagoon just above sea level south of Port Lincoln (Figure 7.1). At Pillie Lake, De Deckker, et al. (1982), found a general decrease in water salinity over the past 5000-6000 years and suggest it was related to a fall in sea level over that time. Shallower water at Little Swamp after about 5000 BP might also have resulted from lowering of the water table by falling sea level.

Results of the pollen and charcoal analyses are presented in Figure 7.4. Some taxa comprising both terrestrial and aquatic plants (e.g., Apiaceae, Ranunculaceae, Haloragis) have been included in the pollen sum. Also on the diagram are curves of the numbers of large charcoal particles and of Chara oospores retained on the 250μm sieve.

The aquatic pollen in the core corresponds well with changes in salinity and water level as indicated by ostracods. The abundance of Myriophyllum pollen in the lowest organic segment (139-133.5cm) and its scarcity above matches the change from fresh to slightly saline conditions. Charophytes, as indicated by numbers of oospores, became more prevalent as water level fell and Cyperaceae were most abundant through the period of lowest water level (75.5-20cm).

The terrestrial pollen in the Little Swamp core shows little change over the 7000 years from the base of the core until the arrival of Europeans. The most abundant pollen grain all through is the largest Casuarina, probably Casuarina stricta (see Kershaw, 1970). To

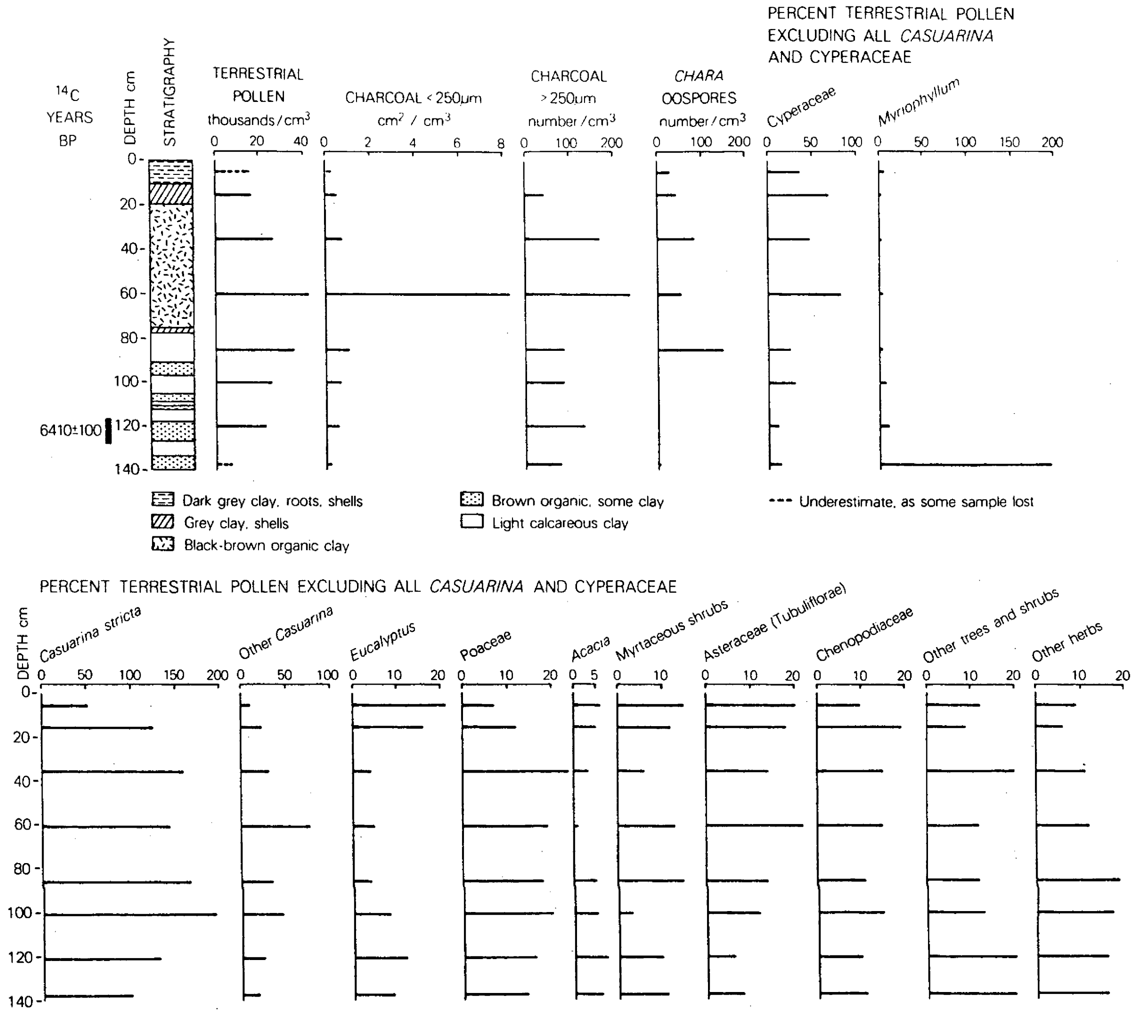


Figure 7.4. Pollen diagram from Little Swamp, showing ^{14}C dates, sediment stratigraphy, concentrations of pollen, charcoal and Chara oospores and abundances of terrestrial and aquatic taxa expressed as percentages of total terrestrial pollen grains excluding all Casuarina species and Cyperaceae. The pollen sum was 100 grains in all samples.

verify this dominance of Casuarina stricta in the surrounding vegetation through all changes in sedimentation conditions in the lake basin, small sediment samples were taken from each stratigraphic layer of the core and mounted directly in water on microscope slides. In every sample, the first or second pollen grain found was from Casuarina stricta. The increasing abundance of Casuarina pollen in the lower part of the core is similar to that recorded at Lashmar's Lagoon (Section 7.1) and Rocky River (Section 7.2) and may reflect the last stages of post-glacial expansion of forests and woodlands (Hope, 1978 and in press). The vegetation throughout the time of deposition of the Little Swamp sediments was very similar to that around Lashmar's Lagoon about 6000-5000 years ago, but the marked change at the latter site from Casuarina stricta woodland to Eucalyptus woodland or shrubland did not occur at Little Swamp until very recently.

The replacement of Casuarina by Eucalyptus around Little Swamp coincides in the top 20cm of core with the presence of pollen from introduced plants (Pinus), from plants which may be introduced (Brassica, Rumex) and with an increase in Plantago pollen which may be from introduced species. There is no pollen from the Liguliflorae (Asteraceae), which is usually found in post-European sediments. Reductions in Chenopodiaceae and Cyperaceae pollen in the top sample may reflect post-European changes in the hydrology of the lake basin, also evident in the stratigraphy. With European use of the land for grazing and cereal crops, the proportion of Poaceae pollen decreased, which suggests that the country was very open and grassy before European settlement. Increased shrubbiness of vegetation following European settlement has been widely reported in Australia (e.g., Howitt, 1890) and the Little Swamp sediments provide palynological evidence that this may have occurred on the Eyre Peninsula.

The area of microscopic charcoal fragments is about the same in all samples except that from 60cm. The large amount in that sample may be due to a single fire burning much of the catchment and followed by rainfall of sufficient intensity to wash charcoal into the swamp, or to the Cyperaceous vegetation of the swamp itself burning. Except at 60cm, pollen and charcoal concentrations appear correlated and, as at Rocky River (Section 7.2), may be related to sedimentation conditions. The area of charcoal per unit volume in all samples, including that from 60cm, is comparable with the range in the lower part of the Lashmar's Lagoon core (*cf.* Fig. 2.4a). The marked change in fire regime about 2500 BP at Lashmar's Lagoon is not evident in the Little Swamp sediments, although the number of samples taken from the latter may be insufficient to show such a change.

The numbers of charcoal particles from each sample retained on the 250μm sieve do not reflect the relative areas of microscopic charcoal. The most noticeable difference is that the 60cm sample contained little more large charcoal than the others. This suggests that it was not burning of the swamp vegetation which produced the abundant microscopic charcoal, but fire in the catchment. In the former case, many more large particles might be expected than if charcoal had been carried downstream from the catchment (Chapter 4).

7.4 Conclusions

Black Creek Swamp is a site which clearly shows limitations in the use of charcoal to reconstruct fire history. Both charcoal and pollen concentrations in the sediments are useful as indicators of deposition and preservation conditions, but while some information about past vegetation may be obtained by identification of small numbers of pollen grains, nothing further can be deduced from charcoal particles.

At Lashmar's Lagoon, the vegetation changed radically about 5000 BP from Casuarina stricta woodland to Eucalyptus shrubland, but at Little Swamp C.stricta persisted as the dominant tree until European settlement. The charcoal content of the sediments suggests that there was no change in fire regime at Little Swamp, but that there might have been more frequent or more intense fires accompanying, and perhaps facilitating, the vegetation change at Lashmar's Lagoon. This interpretation will be discussed further in Chapter 8.3.

It is likely that Aborigines lived on the Eyre Peninsula throughout the Holocene, but disappeared from Kangaroo Island some time after 4300 BP. That charcoal quantities in the Little Swamp sediments are comparable with those in the lower part of the Lashmar's Lagoon core (before 2500 BP), adds some support to the argument from the archaeology and from the theoretical considerations of Chapter 6 that the cessation of Aboriginal burning at Lashmar's Lagoon is marked by a change in fire regime, but not a floristic change in vegetation. Whatever Aboriginal burning practices were, this burning did not change the vegetation from Casuarina woodland to Eucalyptus shrubland at either site. This conclusion is placed in a wider context in Chapter 9.

The change in fire regime about 2500 BP at Lashmar's Lagoon did not lead to major changes in vegetation and it was suggested that this was because the plants were well adapted to fire. If the vegetation throughout the last 5000 years was similar to that at the time of European settlement, then this mallee vegetation must be adapted to a range of fire regimes. In managing National Parks on Kangaroo Island or in mallee areas on the mainland, there appears no need to attempt to impose a particular fire regime. The minimum interval between fires will be determined by the rate of fuel accumulation and the maximum interval by the frequency of ignition. If human interference by lighting or suppressing fires changes the fire frequency within the range of, say, five and fifty years, or perhaps longer, the vegetation would not change markedly, although nothing can be said of the effects on species that do not appear in the pollen record.

Chapter 8

PRESENT AND PAST

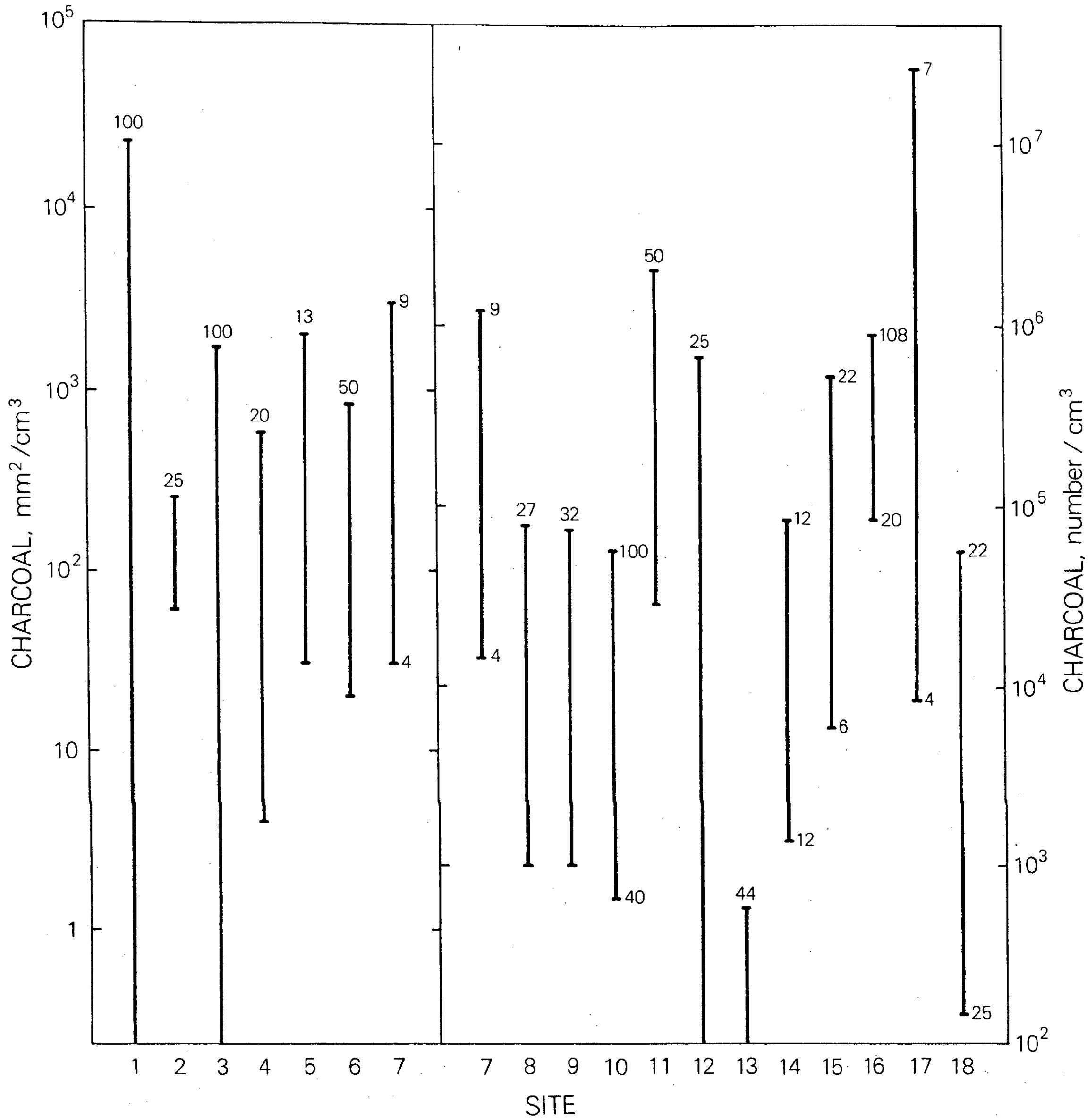
Taking the results from the charcoal collections around present-day fires (Chapter 5) and from the studies of fossil charcoal (Chapter 7), this chapter attempts to answer three questions, two of which have been raised earlier: (1) What is the likely source area of charcoal in lake sediments (Chapters 4 and 6)? (2) Are size distributions of charcoal particles informative (Chapter 3.2)? and (3) What is the best way of presenting charcoal data from a sedimentary record?

8.1 Charcoal quantities

The ranges of charcoal concentrations per unit volume of sediment from eighteen sites in Australia, New Guinea and Vanuatu are plotted on a logarithmic scale in Figure 8.1. Most published sites are included (Ijomba Mire: Hope and Peterson, 1976; Hidden Swamp and Loch Sport Swamp: Hooley, Southern and Kershaw, 1980; Lynch's Crater: Singh, Kershaw and Clark, 1981; Lashmar's Lagoon: Clark and Lampert, 1981, Singh, Kershaw and Clark, 1981, Chapter 7.1; Lake Frome: Singh, 1981a; Aneityum: Hope and Spriggs, 1982; Boomer Swamp and Bridgewater Lagoon: Head, 1983; Telefomin: Hope, 1983a; Kosipe: Hope, 1983b). Lake George (Singh, Kershaw and Clark, 1981, Singh, Opdyke and Bowler, 1981) and Bega Swamp (Polach and Singh, 1980) are excluded as the method used for quantifying charcoal from these sites does not allow results to be compared with others. Also included are results from Black Creek swamp (Chapter 7.2); Little Swamp (Chapter 7.3); Lake Tyrrell, a Victorian salt lake (J. Luly,

Figure 8.1. Ranges of charcoal concentrations in number of particles or area per cubic centimetre of sediment in samples from several sites in Australia, New Guinea and Vanuatu, plotted on a logarithmic scale. Numbers above ranges are the mean number of years represented in each sample; for sites 7, 10 and 14 to 18, figures beside the top and bottom of the range are the approximate number of years in samples with the highest and lowest concentrations. Sites are:

1. Lake Tyrrell (J. Luly, pers. comm.)
2. Princess Charlotte Bay (J. Grindrod, pers. comm.)
3. Black Creek swamp (Chapter 7.2)
4. Bridgewater Lagoon (Head, 1983)
5. Boomer Swamp (Head, 1983)
6. Little Swamp (Chapter 7.3)
7. Lashmar's Lagoon (Singh, Kershaw and Clark, 1981; Chapter 7.1)
8. Hidden Swamp (Hooley, Southern and Kershaw, 1981)
9. Loch Sport Swamp (Hooley, Southern and Kershaw, 1981)
10. Rennex Gap (G.S. Hope, pers. comm.)
11. Lake Frome (Singh, 1981)
12. Lynch's Crater (Singh, Kershaw and Clark, 1981)
13. Star Mountains tarn (G.S. Hope, pers. comm.)
14. Telefomin (Hope, 1983a)
15. Ijomba mire (Hope and Peterson, 1976)
16. Kosipe (Hope, 1983b)
17. Kuk (G.S. Hope, pers. comm.)
18. Aneityum (Hope and Spriggs, 1982)


CHARCOAL, mm²/cm³
10⁵
10⁴
10³
10²
10
1
CHARCOAL, number / cm³
10⁷
10⁶
10⁵
10⁴
10³
10²
SITE
1 2 3 4 5 6 7
7 8 9 10 11 12 13 14 15 16 17 18
100
25
100
20
13
50
9
4
9
4
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32
100
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108
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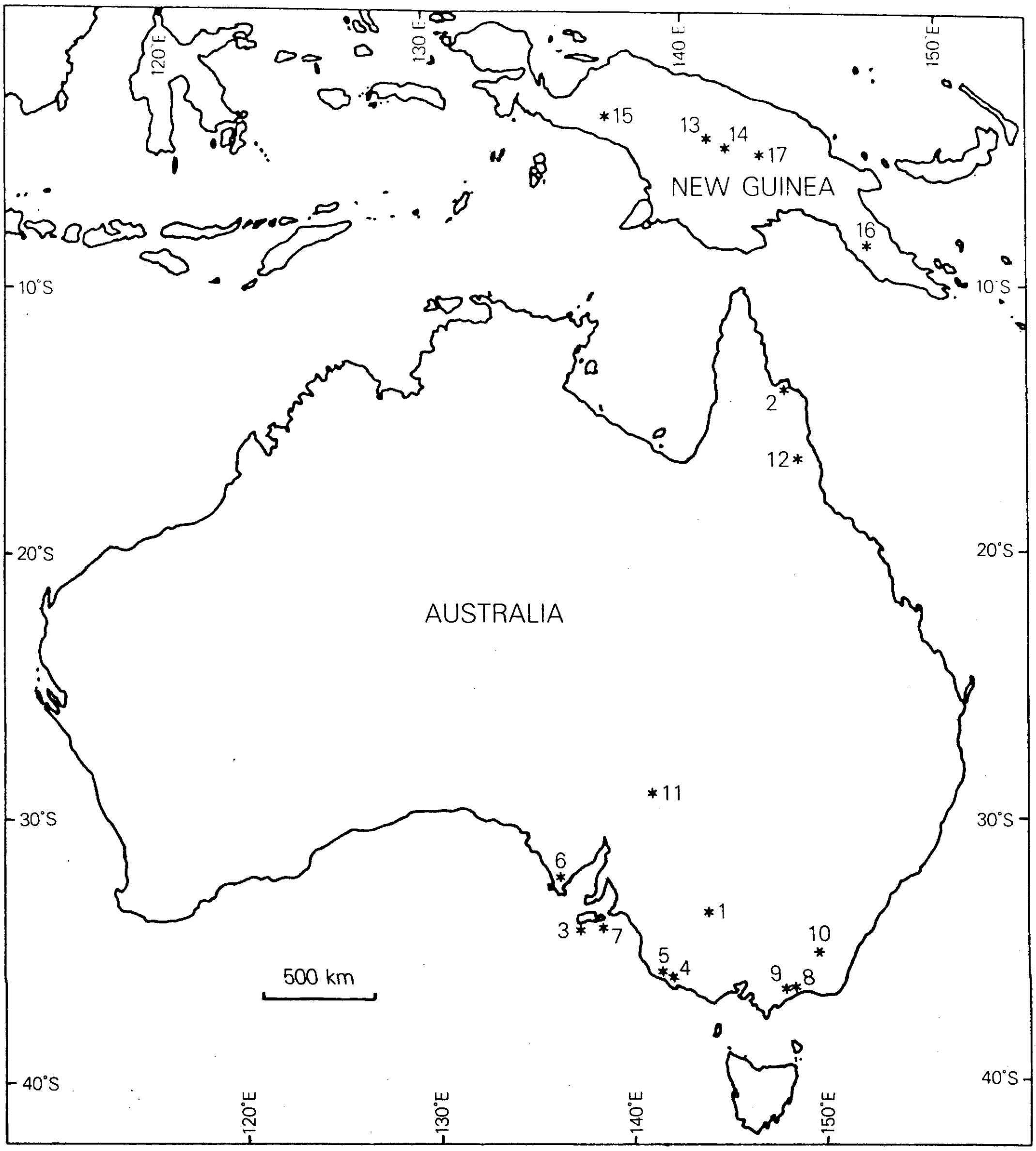


Figure 8.2. Locations of sites in Australia and New Guinea from which data are used in Figure 8.1. Aneityum (20°10'S, 169°47'E; Hope and Spriggs, 1982) in Vanuatu is not included. Sites are:

1. Lake Tyrrell (J. Luly, pers. comm.)
2. Princess Charlotte Bay (J. Grindrod, pers. comm.)
3. Black Creek swamp (Chapter 7.2)
4. Bridgewater Lagoon (Head, 1983)
5. Boomer Swamp (Head, 1983)
6. Little Swamp (Chapter 7.3)
7. Lashmar's Lagoon (Singh, Kershaw and Clark, 1981; Chapter 7.1)
8. Hidden Swamp (Hooley, Southern and Kershaw, 1981)
9. Loch Sport Swamp (Hooley, Southern and Kershaw, 1981)
10. Rennex Gap (G.S. Hope, pers. comm.)
11. Lake Frome (Singh, 1981)
12. Lynch's Crater (Singh, Kershaw and Clark, 1981)
13. Star Mountains tarn (G.S. Hope, pers. comm.)
14. Telefomin (Hope, 1983a)
15. Ijomba mire (Hope and Peterson, 1976)
16. Kosipe (Hope, 1983b)
17. Kuk (G.S. Hope, pers. comm.)

pers. comm.); a subalpine bog at Rennex Gap in the Snowy Mountains, New South Wales (G.S. Hope, pers. comm.); a tarn in the Star Mountains, Papua New Guinea (G.S. Hope, pers. comm.); an agricultural swamp at Kuk in Papua New Guinea (G.S. Hope, pers. comm.) and from a mangrove swamp at Princess Charlotte Bay, north Queensland (J. Grindrod, pers. comm.). Charcoal concentrations have been used rather than annual input as most sites have a complex sedimentary history and few radiocarbon dates. The approximate number of years in samples with the highest and lowest charcoal concentrations are indicated on the diagram for Hope's sites (10 and 13 to 18) and for Lashmar's Lagoon (site 7); for all other sites the mean number of years per sample is included. No account has been taken of the effects of different processing techniques on the amount of charcoal (Chapter 2), nor of differing minimum sizes of charcoal particles included in the counts. Estimates of number and area of charcoal particles have been equated using data from Lashmar's Lagoon. Locations of sites in Australia and New Guinea are shown in Figure 8.2.

The range of charcoal concentrations at most sites extends over two orders of magnitude and the ranges from all but Kosipe and the Star Mountains tarn overlap. Because of the variation within and between sites in sedimentation rate, sedimentation conditions, terrestrial and aquatic vegetation and catchment size, geology and morphology, comparisons such as these are only useful where sites are similar.

One such comparison, between Lashmar's Lagoon and Little Swamp, was made in Chapter 7. It was concluded that charcoal concentrations in the Casuarina woodland phase of the Lashmar's Lagoon history (ca.

6500-5000 BP) suggested a regime of frequent small fires. If this were so, then the amount of charcoal in the Little Swamp sediments, with similar vegetation and a comparable catchment, probably resulted from a similar fire regime. The same conclusion has been drawn from a comparison between Lashmar's Lagoon, Boomer Swamp and Bridgewater Lagoon (Head, 1983). From Figure 8.1, it is evident that the absolute concentrations of charcoal in samples from the last two sites (4 and 5), and from Little Swamp (site 6), Hidden Swamp (site 8) and Loch Sport Swamp (site 9), which show similar vegetation histories, are comparable with the concentrations of charcoal in the lower part of the Lashmar's Lagoon core, so it is likely that the fire regimes at these sites were also similar.

Some samples from four sites contained very little or no charcoal. At Lake Tyrrell (site 1) and Black Creek swamp (site 3), this is probably due to the destruction of charcoal in sediments, but at Lynch's Crater (site 12) and the Star Mountains tarn (site 13) a more likely explanation is that there were no, or very few, fires for extended periods. It was shown in Chapter 6 that increases or decreases in the charcoal content of sediment might result from either an increase or decrease in the interval between fires, depending mainly on vegetation, climate and the sediment sampling scheme. Lashmar's Lagoon provides an example of the case where apparently less frequent fires led to larger quantities of charcoal being deposited in the sediments (Chapter 7.1). Sites in regions where natural fires were extremely rare, due to climate and vegetation, show the opposite change. At Lynch's Crater (Figure 8.1, site 12) and at the New Guinea and Vanuatu sites (sites 13-18), it is likely that large increases in the charcoal content of the sediment are a result of increased fire frequency, an increase which has been attributed to human occupation and burning (Kershaw in Singh, Kershaw and Clark, 1981; Hope and Peterson, 1976; Hope and Spriggs, 1982; Hope 1983a and b; Hope, pers. comm.).

In the following discussion, Lashmar's Lagoon is used as an example of a fossil site for comparison with present-day charcoal production. While the maximum charcoal concentration in Lashmar's Lagoon appears to be higher than at most other sites, the range of charcoal concentrations is representative (Figure 8.1).

The mean number of years represented in each vertical centimetre of sediment sampled from Lashmar's Lagoon is six (Figure 7.2). The range of annual charcoal input to the Lashmar's Lagoon sediment was therefore about 2000-200,000 particles/cm^2/year or 5-500mm^2/cm^2/year. The ranges of concentrations of charcoal in various collections around present-day fires were presented in Table 5.10. These figures may be compared with the amount of charcoal in the Lashmar's Lagoon sediment by calculating the area of receiving surface or the volume of air or water required to supply the amount of charcoal deposited annually on each square centimetre of sediment surface. The maximum area or volume required is the maximum annual input of charcoal to the Lashmar's Lagoon sediments divided by the minimum concentration in the collection; the minimum area or volume is the minimum annual input divided by the maximum concentration. For example, if the range of concentrations of charcoal in water samples collected at a present-day fire was 10-100mm^2/litre, then the range of volumes of water required to supply the amount of charcoal deposited annually on the Lashmar's Lagoon sediments would be 0.05-50 litres. The resulting ranges of values are plotted on a logarithmic scale in Figure 8.3. Where a modern sample contained no charcoal (Nos. 4, 6 and 8), the maximum area or volume required would be infinite.

The values graphed in Figure 8.3 imply that the total charcoal load of a volume of air or water is deposited in one place. In reality, both air and water are usually flowing and only part of the charcoal load is deposited on each unit area of sediment surface. Further, deposition takes place over time, so that charcoal might be deposited from very large volumes of air or water, or charcoal can pass, over time, through the same unit area of water surface to be deposited on the sediment.

It is evident from Figure 8.3 that, even when allowance is made for the time factor, the annual rate of charcoal input to the Lashmar's Lagoon sediments could most easily be achieved by deposition from flowing water carrying charcoal from burned areas of the catchment. For airborne input to be significant, fires must have been close by. The lower part of the Lashmar's Lagoon annual input range could be entirely from smoke from regional fires, without any fires occurring within the water catchment. Considering all the evidence (Chapter 7.1), this is unlikely and it is more probable that the lower charcoal concentrations at Lashmar's Lagoon resulted from frequent small fires, rather than no local fires at all.

The concentration of charcoal in most samples of water flowing from burned catchments (Eden and Bushrangers, Nos. 7, 8 and 9 on Figure 8.3) was higher than might be required for the Lashmar's Lagoon annual input, which suggests that in few, if any, fires was the whole of the catchment of 60 square kilometres burned. This is also evident from a comparison of the amounts of charcoal per unit weight of sediment (Table 8.1). Two factors must be taken into account when making such a comparison:

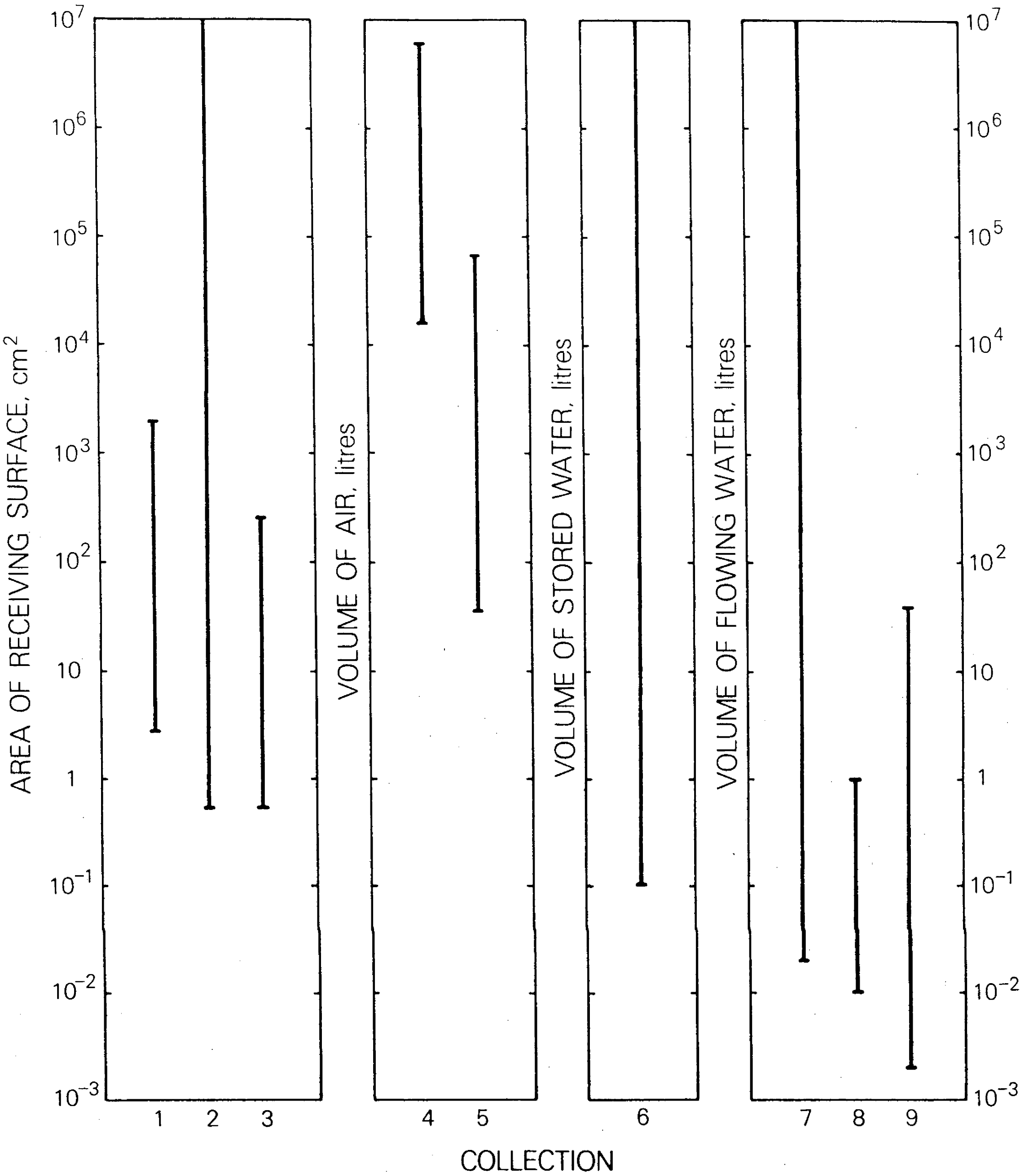


Figure 8.3. A comparison between the amount of charcoal transported from present-day bushfires and past input of charcoal to the Lashmar's Lagoon sediments. Ranges, on a logarithmic scale, indicate the volume of air or water containing charcoal, or the area of receiving surface, required to achieve the range of annual input of charcoal to a square centimetre of sediment surface at Lashmar's Lagoon. Collections from present-day fires are:

1. Black Mountain, slides (Chapter 5.2)
2. Bushrangers catchment, slides (Chapter 5.5)
3. Pollen traps (Chapter 5.1)
4. Bushrangers catchment, Rotorods (Chapter 5.5)
5. Sutton, Rotorods (Chapter 5.4)
6. Sutton and Wollondilly, dams (Chapter 5.4)
7. Eden catchment 4, water samples (Chapter 5.3)
8. Eden catchment 5, water samples (Chapter 5.3)
9. Bushrangers catchment, water samples (Chapter 5.5)

(a) The Lashmar's Lagoon figures are averages of input over several years so peak concentrations of charcoal per unit weight of sediment are probably higher than these estimates suggest.

(b) The geology, slope and vegetation of the Eden and Bushrangers catchments are similar to each other, but very different from those of the Lashmar's Lagoon catchment, so erosion rates and the proportions of charcoal and other suspended sediment might be dissimilar. If the sediment that passed through the Bushrangers catchment weir in the first year after the fire had a mean density of $1.5 g/cm^3$, its total volume would be $4.1 m^3$. If this volume was spread over the area of the Lashmar's Lagoon sediments ($0.47 km^2$), it would form a layer only 0.009mm thick, or 1/185 of the mean annual build-up of sediment in Lashmar's Lagoon (1.7mm). This catchment is sixty times larger than the Bushrangers catchment, so the mean rate of erosion from the Lashmar's Lagoon catchment must be considerably higher than that recorded over sixteen months at Bushrangers. If the amount of charcoal produced by fires on each unit area of ground surface in the two catchments was similar, but the amount of soil eroded from the Lashmar's Lagoon catchment was three times that from Bushrangers, then the ranges of concentration of charcoal per unit weight of sediment (Table 8.1) would be similar, and the highest concentrations of charcoal in the Lashmar's Lagoon sediments could indicate fires which burned the entire catchment.

Table 8.1. Ranges of the amount of charcoal per unit dry weight of sediment at Lashmar's Lagoon (Chapter 7.1) and in water samples from burned catchments on Bushrangers Creek (Chapter 5.5) and near Eden (Chapter 5.3). Numbers of charcoal particles in samples from Eden catchment 5 exclude the two lowest size classes (<19.5μm length) to allow comparison with the Lashmar's Lagoon estimates.

Site	Charcoal
Lashmar's Lagoon	2-1770 particles/mg
" "	ca. 0.025-2.5mm^2/mg
Bushrangers	1-7mm^2/mg
Eden catchment 5	1000-45,000 particles/mg
Eden catchment 4	0-27.5mm^2/mg

Similar comparisons can be made between the amount of charcoal collected around present-day fires (Table 5.10) and that found in the sediments of other sites (Figure 8.1). It is likely that at all sites most charcoal came from fires in the water catchments of the lakes or swamps or from fires outside the water catchments, but close by. Where charcoal concentrations are very low, charcoal may have been destroyed in the sediments, as suggested for Lake Tyrrell and Black Creek swamp, or fires were rare (e.g., Star Mountains tarn and the early period at Lynch's Crater). In the latter case, the small amounts of charcoal in the sediments may well have been transported long distances by wind.

8.2 Size distributions of charcoal particles

When considering the relationship between total numbers of charcoal particles and their total area or length (Chapter 3.2), the possibility was raised that size distributions might be useful for interpreting fossil charcoal records. Waddington's (1969) method of area size-class estimation of the amount of charcoal has been used in several studies (see Chapter 3.1), but most published reports present only the total area of charcoal (*e.g.*, Swain, 1973, 1978; Cwynar, 1978; M. Tolonen, 1978), presumably because size distributions have not provided extra information. This was explicitly stated by Amundson and Wright (1979), who published curves of numbers and areas of charcoal particles in three size classes. Corlett (1979) counted the number of charcoal particles in 11 samples in 7 size classes based on maximum dimension. He found that the majority of particles (from 70% to 90%, mean 82%) fell in the two smallest size classes (10-30μm) and that size distributions were similar in all samples, thus providing no information useful for interpretation. Swain (1973) argued that the small size of fragments in one peak of his charcoal curve as compared with other peaks indicated a year of regional fires rather than local ones. Garrett-Jones (1979) counted numbers of charcoal particles in three area size classes and noted that the three classes did not always show parallel trends. The largest particles, many identifiable as monocotyledon cuticle, were most abundant at times of vegetation disturbance, as indicated by pollen. Byrne, Michaelsen and Soutar (1977 and unpublished) found correlations between large charcoal fragments in cores from the Santa Barbara Channel, California, and major fires on the nearby coastal range, while the influx of smaller particles corresponded with fires in the catchment of the main river system flowing into the Santa Barbara Channel.

R. Nordheim and W.B. Patterson (pers. comm.) suggest that size distributions of charcoal particles are curvilinear, and that the curves for charcoal deposited from local fires differ from those for charcoal deposited from a distance. It was suggested in Chapter 4 that the distribution of numbers of charcoal particles in the size range encountered and identifiable in pollen preparations might best be described as the tail of a normal distribution skewed to the right (lognormal) with a mean less than 1μm and perhaps about 0.1μm. In the charcoal collection described in Chapter 5.2, although numbers of airborne charcoal particles decreased with distance from their source, the size distribution did not change.

Number-size distributions based on 15 length classes for four sets of samples have been determined as described earlier (Chapter 3.2): Black Mountain (airborne charcoal, Chapter 5.2); Eden (waterborne, Chapter 5.3); Bushrangers (airborne, Rotorod collection, Chapter 5.5); and Lashmar's Lagoon (fossil, Chapter 7.1). The number of charcoal particles in each size division was summed over all samples from each of the above sites or collections and the results are plotted against size on logarithmic scales in Figure 8.4. Three area size classes were used by Green (1976, 1981 and pers. comm.; see Chapter 3.2) for analysis of charcoal in samples from four eastern Canadian lakes. The numbers of charcoal particles in each size division summed over all samples from each of these sites are plotted on logarithmic scales in Figure 8.5.

Three models of number-size distributions have been tested on the data in Figure 8.4. In the formulae below, N is the logarithm of the number of charcoal particles in a size division, L the logarithm of the upper limit of that division, and a, b and c are constants.

(1) A power function:

$$N = a + bL.$$

The model of aerosol number-size distributions used by Schütz and Jaenicke (1974) for analysis of Saharan dusts is of this form. Such a distribution would show linear regression when plotted on logarithmic scales as in Figure 8.4.

(2) A lognormal distribution:

$$N = (a/\sigma\ \sqrt{2\pi}).\exp(-b(L-\mu)^2/2\sigma^2) + c,$$

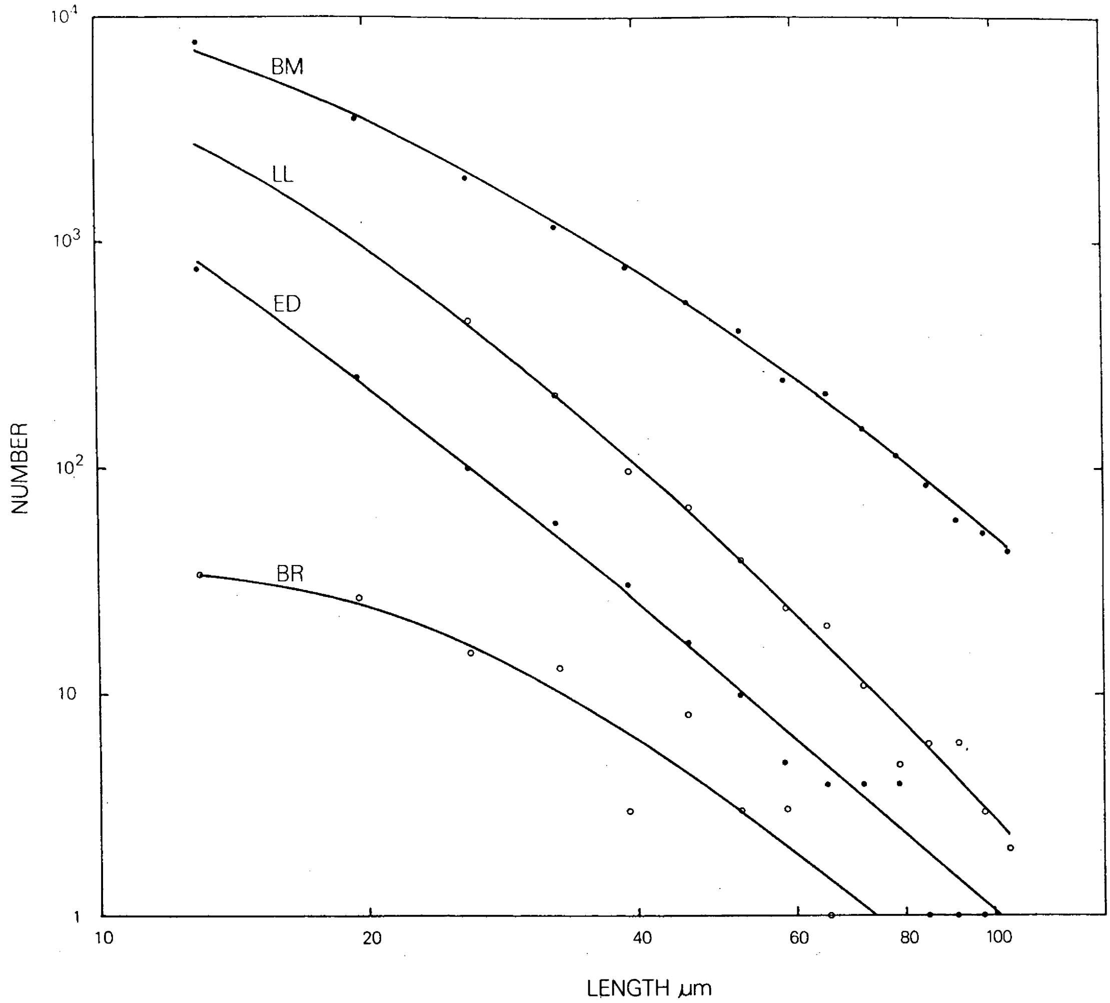
where μ and σ are the mean and standard deviation respectively of the logarithmically transformed distribution. This model has been widely used in grain size studies of sediments (Pettijohn, 1957; Irani and Callis, 1963; Füchtbauer, 1974) and applied to particulates in smoke (Chapter 4).

(3) A loghyperbolic distribution:

$$N = -a\ \sqrt{1 + L^2} + bL + c.$$

This model was introduced by Barndorff-Nielsen (1977), who applied it initially to size distributions of aeolian sands. He also noted that the lognormal distribution is a limit case for the family of loghyperbolic distributions and that these can be derived from a mixture of normal distributions.

Using the POLSTA computer programme of Green (in prep.), these models were fitted to and compared with the data. Means and standard deviations of the sampled distributions were used for the lognormal approximations. All three models showed significant correlations (Pearson's r) between observed and predicted values, but the loghyperbolic distribution provided the closest approximations in all cases and these have been included in Figure 8.4. With only three size classes in Green's data (Figure 8.5) the same analysis was not possible, but power functions fit very well.



<u>Figure 8.4</u>. Size distributions of charcoal particles summed over all samples from each of four sites or collections. The number of particles in each length size division is plotted against the upper limit of that division on logarithmic scales. Symbols indicate observed values, curves are loghyperbolic approximations. The sites and correlation coefficients of the regressions between observed and predicted values are:

BM: Black Mountain; r = 0.9990
LL: Lashmar's Lagoon; r = 0.9930
ED: Eden; r = 0.9864
BR: Bushrangers; r = 0.9381

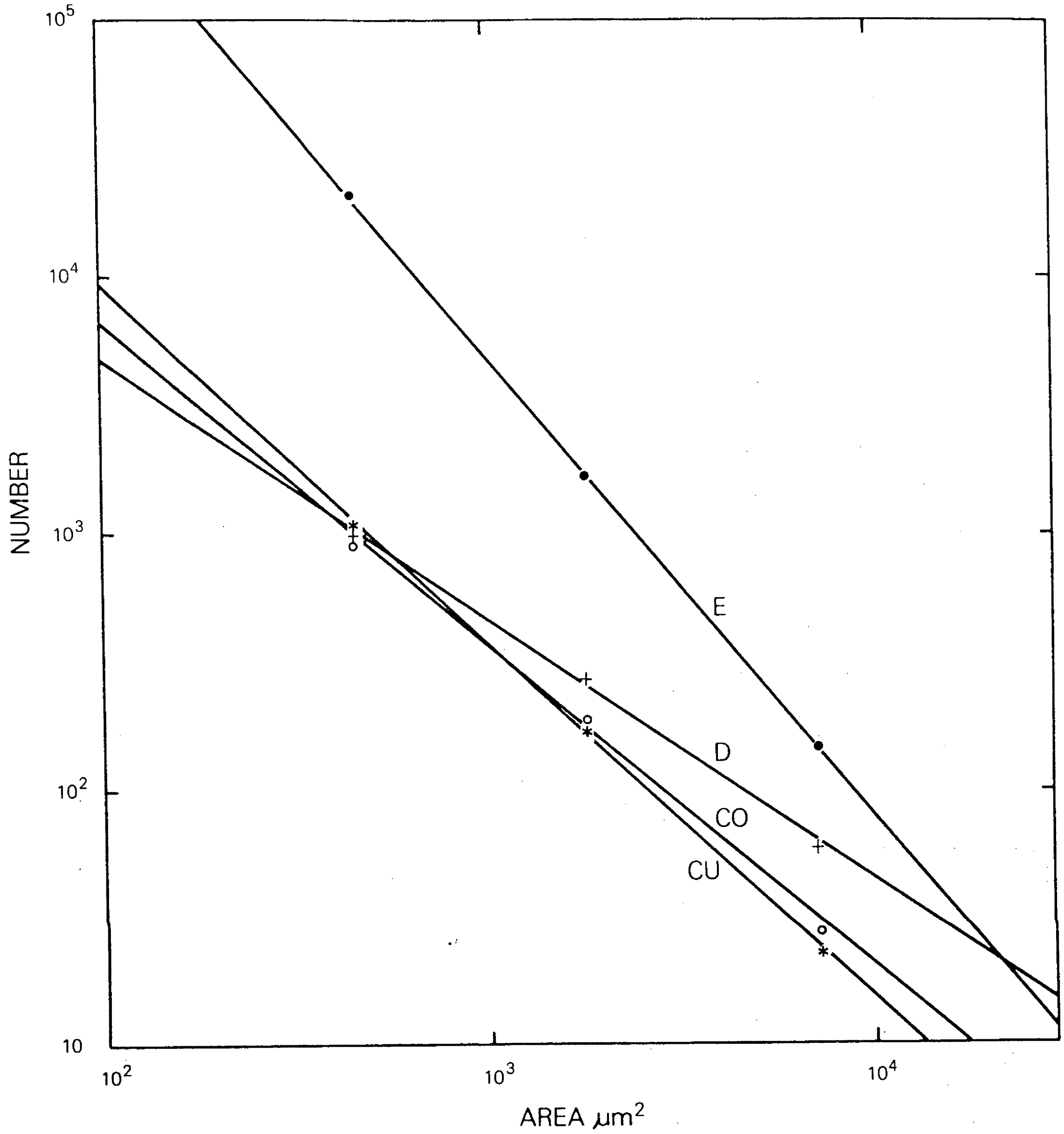


Figure 8.5. Size distributions of charcoal particles summed over all samples from each of four sites. The number of particles in each area size division is plotted against the geometric mean of that division on logarithmic scales. Symbols indicate observed values, lines are power function approximations. Data from Green (1976, 1981 and pers. comm.). The sites and correlation coefficients of the regressions between observed and predicted values are:

E: Everitt Lake; r = 0.9999
D: Duck Lake; r = 0.9994
CO: Collins Lake; r = 0.9988
CU: Curry Pond; r = 0.9996

Lognormal distributions with a range of means and standard deviations were also tested against the observed data. Means of the fitted distributions were chosen between 0.01µm and the observed mean of each sample, and standard deviations between 0.005µm and those of the samples. Values used and the correlation coefficients (Pearson's r) of regressions between predicted and observed values are listed in Table 8.2. Standard deviations of logarithmic distributions cannot be applied to untransformed data, but are included here to indicate their magnitude. Lognormal distributions with means of 0.5, 1, 5 and 10µm gave the best approximations to the observed values of the Black Mountain, Lashmar's Lagoon and Bushrangers samples. The Eden sample differed in that a lognormal distribution with a mean of 0.1µm fitted better than one with a mean of 10µm.

Table 8.2. Correlation coefficients (Pearson's r) of regressions between observed size distributions of charcoal particles from each of four sites or collections and size distributions predicted by a lognormal model with several means and standard deviations. Standard deviations of the logarithmic distributions have been transformed back as an indication of their magnitude only. The maximum correlation for each site is underlined.

Mean µm	Antilog S.D., µm	Correlation coefficient (r) Black Mountain	Lashmar's Lagoon	Eden	Bushrangers Rotorods
10	5	0.9943	0.9905	0.9693	<u>0.9387</u>
5	2	<u>0.9989</u>	0.9926	0.9805	0.9344
1	0.5	0.9974	<u>0.9930</u>	0.9862	0.9250
0.5	0.2	0.9951	0.9926	<u>0.9867</u>	0.9206
0.1	0.05	0.9833	0.9890	0.9828	0.9058
0.05	0.02	0.9586	0.9797	0.9667	0.8824
0.01	0.005	0.7157	0.8371	0.7460	0.6826
20.42*	1.65*	0.9072	-	-	-
33.04*	1.36*	-	0.9072	-	-
16.92*	1.49*	-	-	0.8790	-
22.12*	1.65*	-	-	-	0.8020

* Means and back transformed standard deviations of the sampled distributions.

If the true means of the populations of charcoal particles from which these samples came are well below the observed size range and lie anywhere between 0.1μm and 10μm, then small differences in size distributions over the range 10-100μm are unlikely to be significant. Charcoal particles observed in pollen preparations form a very small fraction of the charcoal produced in fires, and their concentration in smoke, in water and in sediments must be low compared with that of smaller particles (Chapter 4). The samples observed in pollen preparations may be unrepresentative of the whole population, but this will not be known until there are determinations of size distributions of charcoal fragments over the full range, from, say, 0.001μm to 10cm (10^{-9}-10^{-1}m), rather than over part of the range.

From Figure 8.4, it is evident that all four size distributions are similar, but the slopes of the curves differ. The size distribution of the only fossil charcoal included, from Lashmar's Lagoon, is most similar to that of the waterborne charcoal collected at Eden: both have relatively more smaller particles than the two collections of airborne charcoal from Black Mountain and Bushrangers catchment. This agrees with the observations of Byrne, *et al.* (unpublished) that charcoal blown offshore from fires by Santa Ana winds contained larger fragments than charcoal transported by the Santa Clara River. In the discussion of charcoal transport (Chapter 4), it was mentioned that charcoal fragments are likely to be broken up by physical stresses imposed by stream flow. The size distribution of charcoal particles in the Lashmar's Lagoon samples, when compared with airborne and waterborne modern charcoal, suggests that most of the fossil charcoal in these samples was waterborne. But this conclusion is tentative as the differences between the size distributions are not great and the number of sites or collections is so small.

The size distributions plotted in Figure 8.5 are similar, although Duck Lake has relatively more, and Everitt Lake relatively fewer, large particles. Charcoal fragments may be broken up over time in sediments (Chapter 6), and the Everitt Lake sediments provide some evidence for this: the mean area of charcoal particles decreases down the core, with the exception of samples between 402cm and 447cm (Green, pers. comm.). A similar pattern occurs in sediments from Lake George, N.S.W. (Singh, Opdyke and Bowler, 1981; Singh, pers. comm.), where charcoal particles decrease in size from the present day to about 700,000 years ago, but charcoal in even older sediments is larger. In some cases, the mean size and size distributions of charcoal particles may have more to do with sedimentation and preservation conditions than with their source or means of transport.

One of the four samples from Lashmar's Lagoon used for the determination of size distributions contained far more charcoal than the other three (see Figures 2.4 and 7.2). Size distributions in each of the four samples are plotted on logarithmic scales in Figure 8.6. There is no difference between the 310cm sample, where the charcoal has been assumed to come from an extensive wildfire, and the other three samples, where the charcoal might have been produced by less intense and less extensive fires (Chapter 7.1).

One further problem with comparisons of size distributions arises from the experiment reported in Chapter 2. The various procedures used for processing samples have different effects on charcoal, some radically altering the size distribution of the original sample (Figures 2.1 and 2.3).

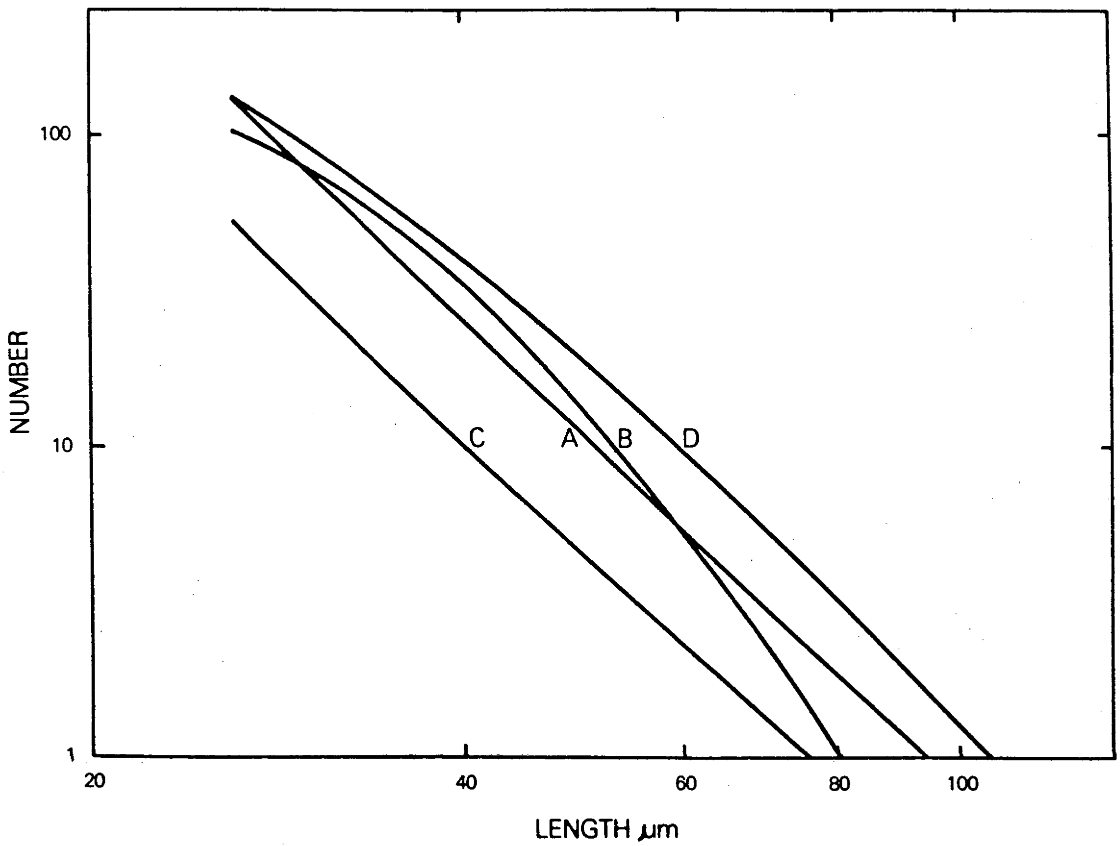


Figure 8.6. Size distributions of charcoal particles in each of four samples from Lashmar's Lagoon. Curves are loghyperbolic approximations to the observed data, plotting number in each length size division against the upper limit of that division on logarithmic scales. Sample depths and correlation coefficients of the regressions between observed and predicted values are:

A: 310cm; r = 0.9742
B: 330cm; r = 0.9839
C: 350cm; r = 0.9386
D: 370cm; r = 0.9910

From all this evidence, the comparison of size distributions of charcoal fragments in sediments shows little promise as an interpretive tool. Although the pattern of breakdown of charcoal, dependent as it is on plant tissue and cell structure (Chapter 2), may be similar world-wide, the original size distribution of fresh charcoal may be modified by physical and chemical processes operating during transport, sedimentation and preservation, and by laboratory preparation of samples for observation. The relative proportions of large and small fragments may be informative (Byrne, et al., unpublished). Further information is needed on the size distributions of charcoal particles in varved sediments from lakes in areas where at least part of the fire history is known from other evidence, such as sites studied by Swain (1973, 1978) and Cwynar (1978).

8.3 Data presentation

Because of the complexities of catchment hydrology there was little correlation between charcoal or sediment concentrations and discharge of water from the Bushrangers and Eden catchments (Chapter 5.5 and 5.3). This, with the continuing drought, made it difficult to discern increases in the charcoal load of water flowing from the catchments after fires. The amount of charcoal per unit weight of sediment proved to be more informative than the amount per unit volume of water. This is because sediment, including charcoal, is suspended only by overland flow while rainfall follows a variety of surface and sub-surface routes before discharging from the catchment. If charcoal is predominantly waterborne to lake sediments, can more information be gained by expressing fossil charcoal quantities as amount per unit weight of sediment rather than amount per unit volume or amount relative to numbers of pollen grains? Swain (1973) and

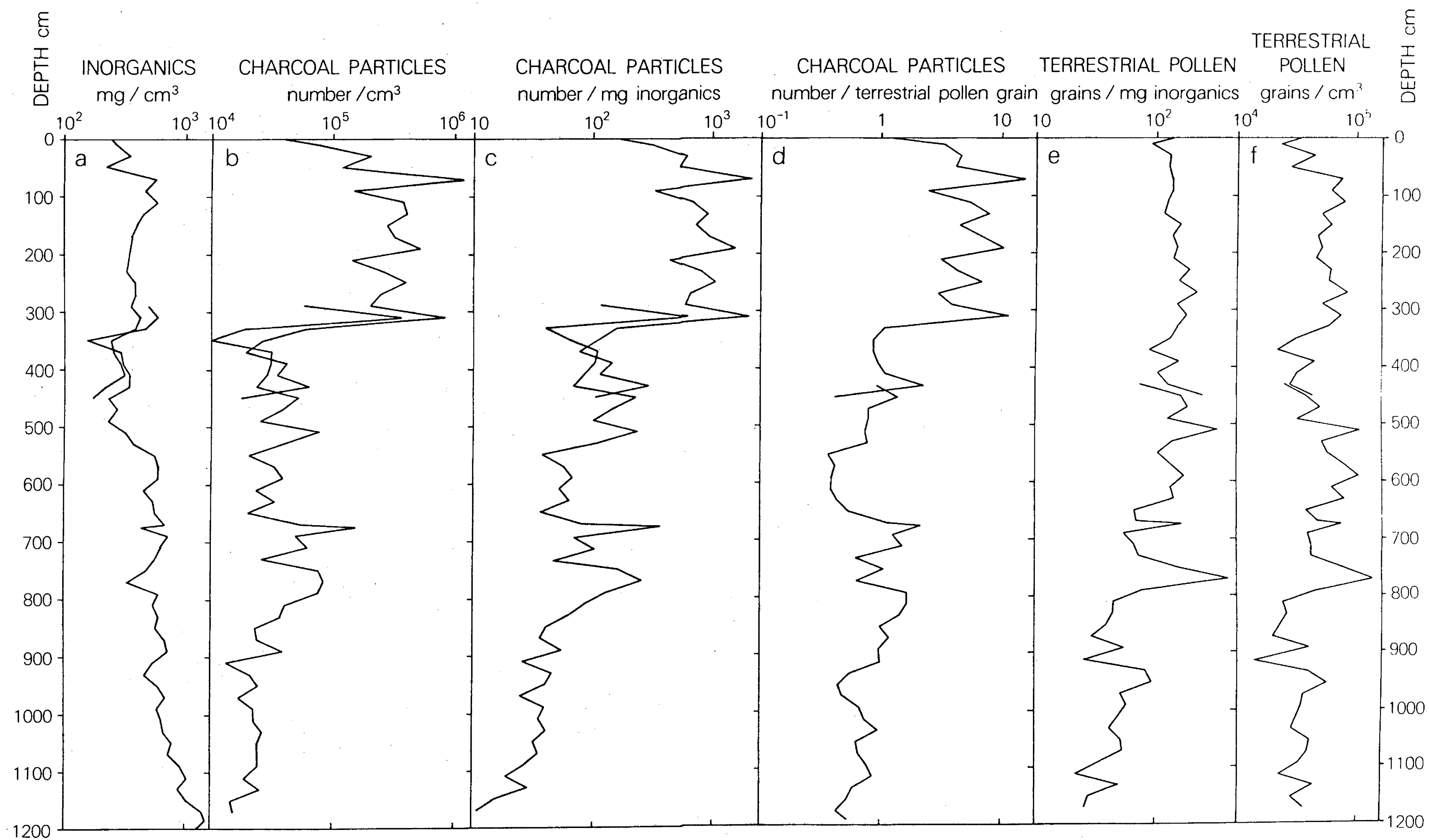
Cwynar (1978) found positive correlations between charcoal influx to sediments and varve thickness, suggesting that, while erosion increased after fires, the increase in charcoal was even greater. Green (1981) found coincident peaks in charcoal and inorganic sediment only where charcoal concentrations were exceptionally high, but he measured the concentration of the inorganic fraction of the sediments, rather than the annual input.

In the Lashmar's Lagoon pollen diagram (Figure 7.2), numbers of charcoal particles and of terrestrial pollen grains per cubic centimetre of sediment were plotted against depth of sediment on an arithmetic scale. The same data is plotted on a logarithmic scale in Figure 8.7 (b and f) to enhance changes in parts of the curves where concentrations are low. Also plotted in Figure 8.7 are logarithms of the dry weight of inorganic sediment per cubic centimetre of sediment (a), the number of charcoal particles (c) and the number of terrestrial pollen grains (e) per milligram dry weight of inorganic sediment and the number of charcoal particles per terrestrial pollen grain (d). The weight of the inorganic fraction of the sediment is used because all inorganics would have originated outside the lake, while most of the organic fraction probably came from plants growing within the lagoon. All fresh-water phases are evident from their low inorganic content (Figures 7.2 and 8.7a). If the sediments contained very little organic matter, or if the input of organics were constant, then the dry weight of the sediment could be used instead of the dry weight of the inorganic fraction.

The sediments are increasingly compressed below 930cm depth (Figure 8.7a) and there is a corresponding decrease in charcoal per milligram of inorganic sediment (Figure 8.7c), although not in

Figure 8.7. Some properties of the Lashmar's Lagoon sediments plotted on a logarithmic scale with depth.

a. Dry weight of inorganic sediment per unit volume of wet sediment.
b. Number of charcoal particles per unit volume of wet sediment.
c. Number of charcoal particles per unit dry weight of inorganic sediment.
d. Number of charcoal particles per terrestrial pollen grain.
e. Number of terrestrial pollen grains per unit dry weight of inorganic sediment.
f. Number of terrestrial pollen grains per unit volume of wet sediment.


DEPTH cm
INORGANICS
mg / cm³
CHARCOAL PARTICLES
number / cm³
CHARCOAL PARTICLES
number / mg inorganics
CHARCOAL PARTICLES
number / terrestrial pollen grain
TERRESTRIAL POLLEN
grains / mg inorganics
TERRESTRIAL
POLLEN
grains / cm³
DEPTH cm
a
b
c
d
e
f

charcoal per cubic centimetre of sediment (Figure 8.7b). Either charcoal in the lower part of the sediment has been destroyed or broken up over time into particles too small to be included in the count, or the input of charcoal was independent of the input of inorganic sediment, as it might be if charcoal was carried to the lagoon in smoke. From the evidence presented in this thesis the former explanation is more likely. This is supported by the smaller decrease with depth in numbers of terrestrial pollen grains per milligram of inorganic sediment (Figure 8.7e); pollen grains may remain intact while charcoal particles may be broken down so that most particles are smaller than the lower size limit of the count (Chapter 6). An alternative explanation is that both the small decrease in pollen concentration and the larger decrease in charcoal concentration result from there having been less woody vegetation around the lagoon in a period when both Casuarina stricta and cf. Melaleuca halmaturorum were increasing in abundance (Figure 7.2a and b).

Expressing numbers of terrestrial pollen grains per milligram of inorganic sediment (Figure 8.7e) rather than per cubic centimetre of sediment (Figure 8.7f) removes fluctuations due to differing amounts of organic material produced within the lagoon. The input of terrestrial pollen has been almost constant since the establishment of Eucalyptus shrubland (630cm and above, Figure 8.7e), reflecting the stability of the vegetation over this period indicated by detailed pollen analysis (Chapter 7.1; Figure 7.2). Over the same time, three phases of differing charcoal input are evident when charcoal is expressed as number per unit weight of inorganic sediment (Figure 8.7c), rather than two when it is expressed as number per unit volume (Figure 8.7b). The lowest phase (630-550cm) corresponds exactly with a period when tree pollen formed a smaller proportion of the total terrestrial pollen than immediately before or after (Figure 7.2b) and when there may have been less woody charcoal produced by fires.

If charcoal is expressed as numbers per unit volume of sediment (Figure 8.7b), the phase between 790cm and 670cm has the highest charcoal concentrations below 310cm. When charcoal is plotted as number per unit weight of inorganic sediment (Figure 8.7c), this phase appears little different from that between 530cm and 320cm. The interpretation of the first curve (Figure 8.7b) would be that fires increased in frequency or extent for some time before Eucalyptus shrubland replaced Casuarina woodland (Chapter 7.1). The second curve (Figure 8.7c) suggests that fires were less frequent or covered a smaller area for some time after the Casuarina decline, or that there was less fuel to burn during this period (630-550cm), as argued above from the smaller proportion of tree pollen.

Expressing charcoal and pollen as amounts per unit weight of inorganic sediment does provide more information than amounts per unit volume of sediment. Plotting charcoal as either number per unit weight of inorganic sediment (Figure 8.7c) or as number per terrestrial pollen grain (Figure 8.7d) allows for changes in sedimentation rate, but the former is preferred as it is independent of pollen production and deposition. Where there are order of magnitude differences between maximum and minimum concentrations, the use of a logarithmic scale may bring out important changes which are not evident on an arithmetic scale. This method is simpler and clearer than superimposing x5 or x10 enlargements of parts of a charcoal concentration curve (e.g., Singh, Kershaw and Clark, 1981), although it does reduce the apparent differences between concentrations of the same order of magnitude.

While these methods of handling data can improve interpretation of long-term fossil charcoal records, detailed fire histories are only possible when annual laminations can be sampled individually. With sediments containing annual laminations, the input of inorganics per year might be a better indicator of erosion rates than varve thickness. If each year's deposition can be sampled, the annual input of all sediment fractions to a unit area of sediment surface can be estimated, and it is not necessary to express quantities of charcoal relative to any other sediment fraction, such as pollen or inorganics.

Chapter 9

POLLEN, CHARCOAL AND ABORIGINAL BURNING IN AUSTRALIA

In Chapter 7, examples were given of the use of charcoal and pollen to reconstruct fire and vegetation histories. It was argued that the change in fire regime about 2500 BP at Lashmar's Lagoon was from a regime of frequent small fires to one of less frequent, more intense fires, and that the cessation of Aboriginal burning of vegetation was the most likely explanation of this change. Assuming from the archaeological evidence that Aborigines were present and lighting fires in the Casuarina stricta woodland phases at both Lashmar's Lagoon and Little Swamp, it was concluded that Aboriginal burning was not responsible for the replacement of Casuarina by Eucalyptus as the dominant tree species. In this chapter, these assumptions and conclusions are placed in the wider context of the use of pollen and charcoal records in Australia to complement or supplement the archaeological evidence of Aboriginal occupation.

Fires have been part of the Australian environment for a very long time. Fusains, believed to be ancient charcoal, are found in coals dating from about ten million to two hundred and fifty million years ago (Kemp, 1981). Adaptations to fire are so prevalent in the most widespread and abundant of Australia's endemic plant genera (Gill, 1975, 1981b), that it is thought they must have evolved with frequent fires. This is not the only possibility, as many of these adaptations also enhance survival through other stresses such as drought, frost, disease and defoliation (Gill, 1975). In pre-human times lightning would have been the most common ignition source, with volcanic eruptions and spontaneous combustion of coal and peat being locally important at times.

The first Aborigines are believed to have migrated to Australia from Southeast Asia at an unknown time before 40,000 years ago (Jones, 1979; White and O'Connell, 1979; Thorne, 1980). Aboriginal burning of vegetation has been widely recorded from European contact to the present day (Hallam, 1975; P.H. Nicholson, 1981; Jones, 1968, 1980) and it is assumed that the earliest inhabitants were able to maintain fire. As Aborigines spread throughout the continent, the number of bushfires, started intentionally or accidentally, must have increased as a new ignition source was added to lightning. The initial impact of Aboriginal burning on the vegetation of Australia might have been considerable and the effects of at least tens of thousands of years of frequent firing profound. These effects should be traceable in the sedimentary pollen and charcoal record.

This thesis has shown that there are many difficulties with interpreting the sedimentary charcoal record in terms of past fire regimes. When dealing with long-term records, several interpretations of the charcoal evidence may be possible, but this is sometimes overlooked when changes are explained in terms of climate, vegetation succession or the actions of people. A further problem is the impossibility of distinguishing fires started by people from those ignited by other means. At the level of resolution of most Australian pollen and charcoal studies, what can be found are long- or short-term changes in vegetation or fire regime, which may or may not be coincident.

Interpretation of the pollen and charcoal evidence has been based, so far, on assumptions about Aboriginal burning and its effects on vegetation, so those assumptions will be considered briefly before the fossil evidence is discussed. Horton (1982) provides more detailed arguments for many of the points mentioned below and discusses a wider range of evidence.

The historical background

Arguments continue about the nature and extent of Aboriginal burning: at one extreme are those who believe Aborigines have always used fire sparingly, judiciously and with complete control; at the other are those who insist Aboriginal burning was and is careless, indiscriminate and as frequent as possible. Historical, ethnographic and anthropological evidence suggest that the reality is somewhere between these extremes (Jones, 1968, 1969, 1975, 1980; Hallam, 1975; P.H. Nicholson, 1981; Horton, 1982). These arguments reflect conflicting and changing views in the white community during the last two hundred years about the role and value of fires in the management of vegetation for exploitation or preservation (Gill, 1981a). Changes in attitudes over time need to be taken into account when interpreting the historical and ethnographic evidence (McBryde and Nicholson, 1978; Horton, 1982), particularly subjective accounts of the size and intensity of fires.

The frequency and areal extent of Aboriginal burning may well have been overestimated and of European burning underestimated. For example, increased density of forest vegetation following European settlement has been attributed to the cessation of frequent burning by Aborigines (Howitt, 1890; Jones, 1968), but other evidence, both historical (Wakefield, 1970) and from fire scars on trees (Costin, 1954; Banks, 1982), suggests that fire frequency, in some areas, increased with the advent of Europeans. But changes in vegetation following European settlement cannot be ascribed to changes in fire frequency alone, as introduced animals and plants radically altered the landscape (Adamson and Fox, 1981; Stockton, 1982; Chapter 7.3). The use of fire by present-day Aborigines (Jones, 1980) provides valuable clues to past burning practices, but it cannot be assumed that current practice is the same as that of the past. Studies of vegetation and fire in sub-tropical woodlands of Kakadu National Park, Northern Territory, suggest that current frequent firing inhibits recruitment to the overstorey (J. Hoare, pers. comm.). Fire frequency must have been lower in the recent past for the vegetation to have developed its present structure.

While all these sources provide some information about Aboriginal burning of vegetation in the past, this knowledge is, and will remain, limited. Just as there is today no one fire regime applied over the entire continent, there would earlier have been a multitude of fire regimes resulting from intentional Aboriginal burning, fire escapes and lightning fires. These fire regimes would have changed over time with shifts in climate, vegetation and population and with changes in technology, food resources and preferences, ritual and other aspects of social life and organization.

Two strands of thought underlie much discussion about the effects of Aboriginal burning on vegetation. The first is the assumption, made by many botanists and archaeologists from wetter northern regions of Europe and North America, that fires are "unnatural" and almost always lit by people (see reviews by Smith, 1970; Hallam, 1975, Chapter 1). The second is the climax theory of vegetation succession (Clements, 1916, 1936). According to Clements, vegetation succession is a series of predictable stages, with each distinct community replacing the one before and preparing the way for the next. Only the final stage, the climax community, is in equilibrium with the environment. Fires are disturbances which return this succession to an earlier stage and prevent, temporarily or permanently, the vegetation from reaching its fullest development.

These two threads were drawn together by Sauer (1956) and Stewart (1956), who suggested that burning by people had created many of the grasslands of the world, preventing them from developing into climax forests. Tindale (1959) applied this argument to Australia. Jackson (1965, 1968) described Tasmanian vegetation in terms of Clementsian succession and argued that, were it not for fires, rainforests would be much more widespread today. Jones (1968, 1969, 1975) elaborated this view, stressing the importance of Aboriginal burning.

Observations of present and past vegetation changes have led to the discarding, or radical modification of, the climax theory of vegetation succession (Connell and Slatyer, 1977; Noble and Slatyer, 1981). Some studies of succession after fire have shown that all species present before a fire regenerate soon after (Purdie and Slatyer, 1976), with differences in growth rates leading to changes in species dominance over succeeding years. Species may be eliminated if the fire regime is such that all reproductive, or potentially reproductive, tissue is destroyed in one or a series of fires, or, if fire is required for regeneration, reproductive tissue fails to survive the interval between fires. Pollen analytical studies of long-term change show vegetation to be far more dynamic than previously thought, changing in composition and structure as individuals and species interact with each other and with their environment. Distinct communities do not succeed each other in predictable sequences, with only the last stage in equilibrium with its environment (M.B. Davis, 1981; D. Walker, 1970, 1982). Fire is not a disturbance which disrupts that equilibrium, returning vegetation to an earlier, unstable successional stage, but rather an integral part of the interaction between plants and their environment. Aboriginal burning must be regarded as one factor in a complex of processes.

The fire regime at any one place over a period of time depends on many things: the composition, structure and flammability of the vegetation; the amount, rate of build-up and moisture content of litter; climate, on all time scales and including seasonality; terrain and soils; and the availability and timing of ignition sources. Present-day fire frequencies in Australia have been mapped and range from almost yearly in northern grasslands to rarely in rainforest and brigalow communities (J. Walker, 1979, 1981). The frequency of fires in forests is limited mainly by moisture content of fuels; in arid and semi-arid regions fires will carry when there is sufficient fuel, usually only after exceptionally good growing seasons (McArthur, 1972; Gill, 1977). The ability of Aborigines to change a fire regime would have been constrained by the environment. The most important change might have been that they could light fires at times of the year when, and in places where, there was usually no other ignition source.

In the following discussion of the fossil evidence, there is a geographical bias which reflects the location of most palynological sites in wetter areas of southeastern Australia. Arguments using evidence from these sites may not be applicable to large areas of the continent, particularly arid regions.

The long-term pollen and charcoal record

Currently, there are only two Australian sites where reconstructions of vegetation and fire history extend back further than 40,000 years: Lake George, on the southern tablelands of New South Wales, and Lynch's Crater, on the Atherton Tableland in northeast Queensland (Singh, Kershaw and Clark, 1981).

In the 350,000 year record from Lake George, Singh found charcoal usually associated with woody sclerophyll vegetation and little or none in grassland periods. The replacement of Casuarina by Eucalyptus as the dominant tree species in a phase ascribed to the last interglacial, and increased quantities of charcoal in sediments laid down since that time, led Singh to suggest that Aborigines might have arrived at Lake George about 120,000 years ago, and that their burning might have been largely responsible for the replacement of fire-sensitive by fire-adapted species. If the larger quantities of charcoal indicate increased incidence of fire, rather than better preservation of charcoal over the shorter term, then these fires did not prevent the re-establishment of Casuarina for a long period, assumed to be an interstadial from 64,000 BP to 22,000 BP, nor an expansion of cool temperate taxa between about 25,000 BP and 8000 BP. Singh draws attention to the similarities between the present interglacial and the period ascribed to the last, but there are differences. Casuarina is relatively scarce in both these periods as compared with earlier wooded phases, but Eucalyptus and myrtaceous shrubs are more abundant in the present interglacial, while cool temperate taxa, which had persisted throughout the preceeding 350,000 years, are completely absent. These vegetation changes could be seen as part of a long-term trend from rainforest to sclerophyll vegetation over much of Australia, beginning in the Tertiary, and the role of fire as an agent of this long-term change remains speculative (Kemp, 1978, 1981; Martin, 1978; Singh, 1981b).

The nature of the Lake George sediments and the lack of precision in their chronology (Singh, Opdyke and Bowler, 1981), with the coarseness of the sampling scheme, the possible destruction of charcoal over time and the complexity of the vegetation changes evident, allow nothing to be said with certainty about fire history. If the commencement of Aboriginal burning is invoked to explain one vegetation change, then continued burning or its absence should be taken into account when explaining subsequent changes.

The sediments so far analysed from Lynch's Crater cover about the last 100,000 years (Kershaw, 1976, 1978; Singh, Kershaw and Clark, 1981). As with Lake George, long-term changes in vegetation are attributed to changes in climate; rainforest flourished in wetter periods, sclerophyll forests and drier rainforest types when the climate was drier. Rainforest gymnosperms disappeared at the time of greatest expansion of sclerophyll taxa, between about 40,000 BP and 25,000 BP, coincident with the first appearance of large amounts of charcoal in the sediments. The initial increase in the amount of charcoal might be due to the lake drying and fires burning the vegetation on its surface, or to increased incidence of fire. If the latter, this might have resulted from a drier climate, more open and more flammable vegetation, Aboriginal burning or a combination of these. If the charcoal in the sediments after 40,000 BP resulted from Aboriginal burning, then these fires did not prevent the return of rainforest in the early Holocene, although they might have been responsible for the extinction of Dacrydium, the reduced abundance of Araucaria and Podocarpus and restriction of drier rainforest types to small patches at the present day.

The "Casuarina decline"

It has been suggested that fire, particularly Aboriginal burning, has been a major factor in the replacement of fire-sensitive trees, including Casuarina, by fire-adapted Eucalyptus (Hooley, Southern and Kershaw 1980; Singh, Kershaw and Clark, 1981; Kershaw, 1981; Singh, 1981b; Walker and Singh, 1981). In the Tertiary, Casuarina was a rainforest associate (Kemp, 1981), but now grows in a wide range of environments (Coyne, 1973). Species of Casuarina, like those of Eucalyptus and other widespread Australian genera, have many mechanisms for surviving fires (A.M. Gill, pers. comm.). It cannot be generalized that the genus Casuarina is fire-sensitive nor less fire-adapted than the genus Eucalyptus. In the long-term records from Lake George and Lynch's Crater, Casuarina was abundant at times when charcoal indicates fires were prevalent (Singh, Kershaw and Clark, 1981).

Pollen analyses from several sites in southeastern Australia show that Casuarina, particularly C.stricta or C.littoralis, was the most abundant taxon, or one of the most abundant, in the early and mid-Holocene (Dodson, 1974a, 1974b, 1975, 1977; Dodson and Wilson, 1975; Hope, 1974; Ladd, 1978, 1979; Hooley, Southern and Kershaw, 1980; Singh, Kershaw and Clark, 1981; Head, 1983; Chapter 7). At some sites, this dominance of C.stricta or C.littoralis was maintained until European settlement; at others, Eucalyptus replaced Casuarina much earlier, but not synchronously throughout the region. Where charcoal has been analysed along with pollen, charcoal peaks may or may not accompany the decline of Casuarina (Hooley, Southern and Kershaw, 1980; Head, 1983; Chapter 7).

It is likely that Aborigines were living and burning in these Casuarina woodlands, at least intermittently, through the Holocene. Head (1983) suggests that as Casuarina woodlands are naturally open, Aborigines may rarely have burned them. From archaeological evidence it is likely that Aborigines lived on the southern Eyre Peninsula from the late Pleistocene to the present-day, but disappeared from Kangaroo Island some time after 4300 BP (Lampert, 1981). At Lashmar's Lagoon on Kangaroo Island, Casuarina stricta woodlands disappeared about 5000 BP (Chapter 7.1), but at Little Swamp on the Eyre Peninsula, they persisted throughout the time of Aboriginal occupation (Chapter 7.3). At Wyrie Swamp in southeastern South Australia, the time of most intensive Aboriginal usage, as indicated by the number of artefacts found, was also that of maximum extent of Casuarina stricta woodland (Dodson, 1975, 1977).

There is no direct correlation between the decline of Casuarina in the Holocene and Aboriginal burning, but European settlement had a devastating effect on Casuarina woodlands, probably by a combination of cutting and burning, with sheep grazing on foliage and seedlings. The early Holocene spread of Casuarina into grasslands and shrublands abundant at the height of the last glacial (Hope, 1978, in press; Chapter 7.1) and its later displacement by Eucalyptus may have been part of a natural sequence of competing species in a changing environment. Aboriginal burning must have been part of that environment, but its importance cannot be deduced from the evidence so far available.

Cave Bay Cave

Cave Bay Cave, on Hunter Island, off the northwest coast of Tasmania, has been occupied intermittently by Aborigines over the last 23,000 years (Bowdler, 1979). Hope (1978) reconstructed the vegetation history from pollen in the cave deposits. The only vegetation changes associated with periods of occupation were reductions in ferns and _Tasmannia_ (formerly _Drimys_), which probably grew within or near the mouth of the cave. Other changes followed regional climatic trends and the rise in sea level. Charcoal was found throughout the deposit and, as Hope points out, Aborigines might have been in the area and firing the vegetation without occupying the cave. Either the fire regime remained fairly constant over the 23,000 years, or changing fire regimes with fluctuations in population or usage had little or no effect on the vegetation.

The vegetation throughout most of the period of deposition in Cave Bay Cave appears to have been well adapted to fire. Changing the interval between fires from, say, thirty years to three years, or vice versa, may, with some exceptions, have little effect on fire-adapted vegetation, or have effects which are imperceptible at the level of resolution of most pollen analyses, in which subtle vegetation changes might be missed entirely. An example of this is provided by Lashmar's Lagoon, where a marked change in fire regime after 2500 BP, as indicated by the charcoal content of the sediments, was not accompanied by changes in pollen from vegetation made up of fire-adapted taxa (Chapter 7.1).

Late Pleistocene grasslands and Holocene forests

Hope (in press) has collated the information from various pollen analysis sites in southeastern Australia and mapped a reconstruction of regional vegetation distributions between about 22,000 BP and 16,000 BP, at the height of the last glacial. Compared with the present day, grasslands, shrublands and very open woodlands covered vast areas, while forests of all kinds were severely restricted. After 16,000 BP, forests spread from their remaining areas and smaller refugia until the present pattern was established by about 5000 BP. If Aboriginal burning played a part in the establishment of grasslands at the height of the last glacial, then that burning did not stop the advance of the forests as the climate warmed. Aboriginal burning might have affected the rate of change by opposing or complementing the climatically determined direction of change (Macphail, 1980). It is impossible to know whether these forests, particularly rainforests and wet sclerophyll forests, would have been more widespread had there been no Aboriginal burning.

Macphail (1980), summarizing the vegetation history of Tasmanian forests, concluded that there was a long-term relationship between climate and fire frequency independent of vegetation. He attributes the replacement of temperate rainforest by sclerophyll forests over the last 5000-6000 years to changes in climate, soil fertility and fire frequency which complement each other. Aboriginal burning may have been partly responsible for an increased fire frequency, but was not the sole cause of the retreat of the rainforest.

Conclusion

From this evidence, it is likely that Aborigines neither created nor maintained vast areas of grassland, although their burning may have been responsible for the continuation of patches of grassland or woodland within larger forested regions. Climate has been and is far more important than fire in determining the distribution of Australian vegetation, but Aboriginal burning might have affected the rate of vegetation change. The complex interaction and interdependence of fire, climate, soils and vegetation make it extremely difficult to distinguish effects of Aboriginal burning. So much of Australia's vegetation is adapted to fires that it may have been only in the fire-sensitive vegetation of wetter areas that the commencement of Aboriginal burning had much impact. An excellent example is provided by the work of Corlett (1979), who reconstructed, using pollen and charcoal analyses, the history of human impact through fire on the subalpine vegetation of Mt Wilhelm in Papua New Guinea.

Until fine resolution charcoal analyses provide information about specific fire regimes, conclusions about fire histories will continue to be based on assumptions about Aboriginal burning. A major problem is confusion of scale. Observations of the Australian environment and historical and ethnographic records cover little more than two hundred years; most pollen analyses span thousands of years, with one or two samples from each two hundred years. Changes evident on one scale might not be apparent on the other, while conclusions from one set of evidence might be inappropriate to the other.

While much has been learned about the effects of Aboriginal burning on the vegetation of Australia, far more information can be gained if the interpretation of the sedimentary charcoal record is based on a better understanding of the complexities involved. The aim of charcoal analysis is to determine the long-term effects of different fire regimes on vegetation. That aim is defeated if interpretation of the pollen and charcoal record is based on prior assumptions, unsupported by evidence, about the responses of vegetation to fire and the relationship between fires and sedimentary charcoal.

Chapter 10

CONCLUSIONS

Several approaches have been taken to the problems of deducing fire history from charcoal preserved in lake and swamp sediments, and relating fire history to vegetation history reconstructed from the pollen record. The main conclusions are:

1. Charcoal can be removed or broken up by physical, chemical or biological means during transport from fires, storage in soil or sediments, or by sample preparation procedures. It may be broken into fragments too small to be distinguished under a light microscope or smaller than the lower size limit of particles included in estimates of quantity. (Chapter 2)

2. Standard pollen preparation procedures or treatment for one hour in hot concentrated nitric acid are suitable for concentrating charcoal in sediment samples as most black particles that might be confused with charcoal are removed. Time is saved if the same preparations are used for both pollen and charcoal analyses. Particles carbonized by means other than fire cannot be distinguished from charcoal. Individual steps of the preparation procedure affect charcoal differently, so if quantitative comparisons are to be made between samples, then the same preparation procedure must be used for all. (Chapter 2)

3. Methods for estimating numbers or projected areas of charcoal particles in pollen preparations are probably equally valid for comparisons between samples, although how these parameters relate to volumes or weights of charcoal is not known. The point count method is recommended above all others as it is simpler to use, faster and

counting errors can be estimated easily. (Chapter 3)

4. Point count estimates of volume of charcoal from thin sections of sediments will allow detailed reconstructions of fire histories when methods for preparing thin sections have been perfected. The main limitation will be that black particles other than charcoal will remain in the sections. Volumes of other constituents of sediments may also be estimated by point counting. (Chapter 3.1)

5. Size distributions of charcoal particles do not appear to provide useful information, but further research is necessary on this point. (Chapters 3.2, 4 and 8.2)

6. The expression of charcoal quantities as concentration per unit dry weight of inorganic sediment is more informative than as concentration per unit volume of wet sediment. The use of a logarithmic scale to plot data, rather than an arithmetic scale with superimposed exaggerations, may be less confusing where order of magnitude differences in charcoal concentrations occur within a set of samples. (Chapter 8.3)

7. Microscopic charcoal fragments cannot usually be attributed to a plant taxon, although diagnostic morphological features may occasionally be evident. Charred fragments of monocotyledon epidermis are distinguishable and may be identifiable. (Chapters 5.4 and 6)

8. It is not possible to use models of charcoal transport to deduce, from a charcoal assemblage in sediments, the location of the fire from which the charcoal came. (Chapter 4)

9. There is a general background of charcoal carried long distances in smoke or dust, but most charcoal in lake sediments has been transported by water. Because charcoal is transported principally by water, bogs do not contain records of fires in surrounding areas, but, if sometimes flooded or burned, can contain an incomplete record.

(Chapters 4, 5 and 8.1)

10. Most charcoal produced by a fire remains in the burned area. The amount subsequently removed by runoff and deposited in sediments will depend as much on the timing and intensity of rainfall as on the characteristics of the fire and the amount of charcoal produced. Charcoal in sediments provides a record of fire-rainfall events, not just of fires, and individual fires may be under-represented in, or missing entirely from, the sedimentary record. (Chapters 4, 5 and 6)

11. The charcoal catchment of a lake is the water catchment and areas close to, but outside, the water catchment. It may not be the same as the pollen catchment. If a fire has burned only part of the pollen catchment, then the pollen record of post-fire regeneration of vegetation will be obscured. (Chapters 4 and 6)

12. The sedimentary charcoal record of any one fire can be either sharply defined or attenuated, depending on the distribution in time of rainfall, the rates of vegetation regeneration and litter accumulation, the distance charcoal travels to a sedimentary basin, the nature of the stream channel and mixing of sediments by biotic, physical or chemical means. (Chapters 4 and 6)

13. The sediment sampling scheme (the number of years of deposition within and between samples) affects the apparent charcoal record, which may or may not reflect the true fire history. When dealing with anything less precise than annual charcoal input, only major changes in charcoal quantities should be considered significant, but the possibility will remain that even these may be artefacts. (Chapter 6)

14. Depending on vegetation type and the rate of fuel accumulation, either more or less frequent fires can increase the amount of charcoal produced over a period of time and, hence, the amount of charcoal that can be carried to a deposition site. (Chapters 6 and 7)

15. Changes in fire regime do not necessarily lead to long-term changes in vegetation, nor are changes in vegetation necessarily accompanied by changes in fire regime. (Chapter 7)

16. At some sites changes in charcoal concentrations reflect only changes in sedimentation or preservation conditions and cannot be used to reconstruct fire histories. (Chapter 7)

17. At sites with comparable catchments and vegetation, similar or different fire regimes may sometimes be identified by comparison of the amounts of charcoal in sediments. (Chapter 8.1)

18. The impact on vegetation of people using fire might be clearly distinguishable only in areas where natural fires were previously absent or rare. (Chapters 8.1 and 9)

19. The interactions between climate, soils, vegetation, fire and people are complex and dynamic in both time and space. Simplistic interpretations of the pollen and charcoal record in terms of the effects of fires, particularly Aboriginal burning in Australia, on vegetation, are inadequate. (Chapter 9)

20. Available evidence suggests that Australian Aborigines neither created nor maintained large areas of grassland and that climate has been more important than fire in determining vegetation distribution. (Chapter 9)

Further research is required in several areas, both to follow up the work described in this thesis and to provide a better understanding of the relationship between fire and vegetation. The main areas are: (a) the conditions under which plant material can be carbonized by means other than fire; (b) the use of size distributions of charcoal particles as indicators of the proximity of fires to deposition sites; (c) comparisons between the various methods of quantifying charcoal in pollen preparations;

(d) techniques for preparing thin sections of sediments so that the annual input volume of charcoal can be estimated by point counting; (e) the deposition in sediments of charcoal from present-day and historical fires; and (f) the effects of different fire regimes on individual plant species, as well as on vegetation communities.

Many of the observations described in this thesis, and the conclusions drawn from them, apply to pollen as well as charcoal, particularly those relating to transport, deposition and sediment sampling. More research is needed on the relative importance of wind and water in carrying pollen to lake sediments.

As techniques are developed for fine sampling of annually laminated sediments, it will be possible to study past responses of vegetation to a single fire or a series of fires and to reconstruct detailed fire histories. Information on this time-scale is essential if the long-term record is to be interpreted in terms of the effects of fire regimes on vegetation. That is the first goal in studying fire history; the second is to explain why fire regimes changed.

Variations in charcoal quantities in sediments might result from changes in any of the variables constituting a fire regime or from changes in climate, particularly rainfall regime, or in vegetation and, hence, fuel type and abundance. The sedimentary charcoal evidence alone is insufficient for reconstructing fire history and must be used in conjunction with other evidence for past environmental stability or change. This thesis has shown that, although there is no simple correspondence between the charcoal record and the true fire history, the number of interpretations of the charcoal evidence can be reduced to a few. The most likely explanation can be selected after considering all available evidence, with some understanding of the processes of charcoal production, transport, deposition and preservation and the effects of sampling and laboratory processing on results.

In countries such as Australia, where the landscape has been altered by Europeans for a comparatively short period, it is possible to discover the role of fire in shaping the vegetation that existed when the first European settlers arrived. Present-day vegetation and fire regimes may not be adequate guides to either the past or the future. If fire is to be used to manage vegetation, it is essential to know whether vegetation and fire regimes remained the same or changed over the thousand or so years before European settlement. Fine resolution, preferably year by year, pollen and charcoal analyses of the abundant sediments from the most recent period can provide this knowledge. Over the longer term, it may be possible to discern the effects on vegetation of Aboriginal land use, but this is difficult because older sediments are less abundant than recent ones and there has been more time for diagenesis. Where the sediments allow, a combination of sampling schemes is recommended, with fine resolution analyses of sediments from critical periods supplementing the record from sampling with many years of deposition within and between samples.

Fire is part of the dynamic interaction between plants and their environment. The sedimentary charcoal record, although imperfect, can help clarify the complexities of that interaction and provide information on the long-term effects of fire regimes on vegetation.

REFERENCES

Adamson, D.A., and Fox, M.D., 1981. Change in Australasian vegetation since European settlement. In J.M.B. Smith (ed.), A History of Australasian Vegetation, pp. 109-146. McGraw-Hill, Sydney.

Alexander, M.E., 1979. Bibliography and a Résumé of Current Studies on Fire History. Great Lakes Forest Research Centre, Sault Ste. Marie, Ontario, Report O-X-304.

Amundson, D.C., and Wright, H.E., 1979. Forest changes in Minnesota at the end of the Pleistocene. Ecological Monographs, 49, 1-16.

Baillie, P.J., 1978. Port Lincoln and District. A Pictorial History. Lynton Publications, Blackwood.

Banks, J.C.G., 1982. The use of dendrology in interpreting the dynamics of snow gum forest. Ph.D. thesis, Australian National University, Canberra.

Barndorff-Nielsen, O., 1977. Exponentially decreasing distributions for the logarithm of particle size. Proceedings of the Royal Society of London., A, 353, 401-419.

Beadle, N.C.W., and Costin, A.B., 1952. Ecological classification and nomenclature. Proceedings of the Linnaean Society of New South Wales, 77, 61-82.

Birks, H.J.B., and West, R.G. (eds.), 1973. Quaternary Plant Ecology. Blackwell, Oxford.

Biswell, H.H., 1973. A summary of research on smoke and air pollution from forest and wildland burning. In Proceedings of the 17th Annual Arizona Watershed Symposium.

Black, J.M., 1943-1957. Flora of South Australia. South Australian Government Printer, Adelaide, 4 volumes.

Blong, R.J., and Gillespie, R., 1978. Fluvially transported charcoal gives erroneous ^{14}C ages for recent deposits. Nature, 271, 739-741.

Blong, R.J., Riley, S.J., and Crozier, P.J., 1982. Sediment yield from runoff plots following bushfire near Narrabeen Lagoon, N.S.W. Search, 13, 36-38.

Bonny, A.P., 1978. The effect of pollen recruitment processes on pollen distribution over the sediment surface of a small lake in Cumbria. Journal of Ecology, 66, 385-416.

Bowdler, S., 1979. Hunter Hill, Hunter Island. Ph.D. thesis, Australian National University, Canberra.

Bowler, J.M., 1978. Glacial age aeolian events at high and low latitudes: A Southern Hemisphere perspective. In E.M. van Zinderen Bakker (ed.), Antarctic Glacial History and World Palaeoenvironments, pp. 149-172. A.A. Balkema, Rotterdam.

Bowler, J.M., Hope, G.S., Jennings, J.N., Singh, G., and D. Walker, 1976. Late Quaternary climates of Australia and New Guinea. Quaternary Research, 6, 359-394.

Bradbury, J.P., and Waddington, J.C.B., 1973. The impact of European settlement on Shagawa Lake, Northeastern Minnesota, U.S.A. In H.J.B. Birks and R.G. West (eds.), Quaternary Plant Ecology, pp. 289-307. Blackwell, Oxford.

Burbidge, N.T., and Gray, M., 1976. Flora of the Australian Capital Territory. Australian National University Press, Canberra.

Burgess, J.S., Olive, L.J., and Rieger, W.A., 1980. Sediment discharge response to fire in selected small catchments - Eden, N.S.W. In Hydrology and Water Resources Symposium, pp. 157-161. Institution of Engineers, Australia, National Conference Publication No.80/9.

Burgess, J.S., Rieger, W.A., and Olive, L.J., 1981. Sediment yield change following logging and fire effects in dry sclerophyll forest in southern New South Wales. In Erosion and Sediment Transport in Pacific Rim Steeplands, pp. 375-385. International Association of Hydrological Sciences Publication No.132, Christchurch.

Burne, R.V., 1982. Relative fall of Holocene sea level and coastal progradation, northeastern Spencer Gulf, South Australia. BMR Journal of Australian Geology and Geophysics, 7, 35-45.

Burrows, K., 1979. Climate. In M.J. Tyler, C.R. Twidale and J.K. Ling (eds.), Natural History of Kangaroo Island, pp. 53-64. Royal Society of South Australia, Adelaide.

Byrne, R., Michaelsen, J., and Soutar, A., 1977. Fossil charcoal as a measure of wildfire frequency in Southern California: A preliminary analysis. In H.A. Mooney and C.E. Conrad (eds.), Proceedings of the Symposium on the Environmental Consequences of Fire and Fuel Management in Mediterranean Ecosystems, pp. 361-367. United States Department of Agriculture Forest Service General Technical Report WO-3, Washington.

Byrne, R., Michaelsen, J., and Soutar, A., unpublished. Fossil charcoal from varved sediments in the Santa Barbara Channel: an index of wildfire frequencies in the Los Padres National Forest (735 A.D. to 1520 A.D.).

Churchill, D.M., 1968. The distribution and prehistory of Eucalyptus diversicolor F. Muell., E.marginata Donn ex Sm. and E.calophylla R. Br. in relation to rainfall. Australian Journal of Botany, 16, 125-151.

Clark, R.L., 1976. Vegetation history and the influence of the sea at Lashmar's Lagoon, Kangaroo Island, South Australia, 3000 BP to the present day. B.Sc. (Hons.) thesis, Monash University, Melbourne.

Clark, R.L., 1981. The prehistory of bushfires. In P.J. Stanbury (ed.), Bushfires - Their Effect on Australian Life and Landscape, pp. 60-73. Macleay Museum, University of Sydney.

Clark, R.L., 1982. Point count estimation of charcoal in pollen preparations and thin sections of sediments. Pollen et Spores, 24, 523-535.

Clark, R.L., 1983. The pollen and charcoal evidence for the effects of Aboriginal burning on the vegetation of Australia. Archaeology in Oceania, to appear.

Clark, R.L., and Lampert, R.J., 1981. Past changes in burning regime as markers of Man's activity on Kangaroo Island, South Australia. Terra Australis, 5, 186-189.

Clements, F.E., 1916. Plant Succession. Carnegie Institute, Washington, Publication No. 242.

Clements, F.E., 1936. Nature and structure of the climax. Journal of Ecology, 24, 252-284.

Close, R.C., Moar, N.T., Tomlinson, A.I., and A.D. Lowe, 1978. Aerial dispersal of biological material from Australia to New Zealand. International Journal of Biometeorology, 22, 1-19.

Conaghan, H.F., 1940. The effect of the temperature of carbonisation of wood on some of the properties of the charcoal produced. N.S.W. State Fuel Research Commission Report.

Connell, J.H., and Slatyer, R.O., 1977. Mechanisms of succession in natural communities and their role in community stability and organization. American Naturalist, 111, 1119-1144.

Conrad, C.E., and Oechel, W.C., (eds.) 1982. Proceedings of the Symposium on Dynamics and Management of Mediterranean-Type Ecosystems. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, General Technical Report PSW-58.

Cope, M.J., and Chaloner, W.G., 1980. Fossil charcoal as evidence of past atmospheric composition. Nature, 283, 647-649.

Corlett, R.T., 1979. Human impact on the subalpine vegetation of Mt. Wilhelm, Papua New Guinea. Ph.D. thesis, Australian National University, Canberra.

Costin, A.B., 1954. A Study of the Ecosystems of the Monaro Region of New South Wales. New South Wales Government Printer, Sydney.

Coyne, P.D., 1973. Some aspects of the autecology of Casuarinas, with particular reference to nitrogen fixation. Ph.D. thesis, Australian National University, Canberra.

Crowley, G.M., 1981. The Late Quaternary environmental history of the Lake Bolac region of Western Victoria, and its implications for Aboriginal occupation. B.Sc.(Hons.) thesis, Monash University, Melbourne.

Cwynar, L.C., 1978. Recent history of fire and vegetation from laminated sediment of Greenleaf Lake, Algonquin Park, Ontario. Canadian Journal of Botany, 56, 10-21.

Daily, B., Milnes, A.R., Twidale, C.R., and J.A. Bourne, 1979. Geology and geomorphology. In M.J. Tyler, C.R. Twidale and J.K. Ling (eds.), Natural History of Kangaroo Island, pp. 1-38. Royal Society of South Australia, Adelaide.

Davis, M.B., 1963. On the theory of pollen analysis. American Journal of Science, 261, 897-912.

Davis, M.B., 1981. Quaternary history and the stability of forest communities. In D.C. West, H.H. Shugart and D.B. Botkin (eds.), Forest Succession: Concepts and Application, pp. 132-153. Springer-Verlag, New York.

Davis, R.B., 1967. Pollen studies of near-surface sediments in Maine lakes. In E.J. Cushing and H.E. Wright (eds.), Quaternary Paleoecology, pp. 143-173. Yale University Press, New Haven.

Davy, P.J., and Miles, R.E., 1977. Sampling theory for opaque spatial specimens. Journal of the Royal Statistical Society, B, 39, 56-65.

De Deckker, P., 1981a. Ostracods of athalassic saline lakes. A review. Hydrobiologia, 81, 131-144.

De Deckker, P., 1981b. Taxonomy, ecology and palaeoecology of ostracods from Australian inland waters. Ph.D. thesis, University of Adelaide.

De Deckker, P., 1981c. Taxonomy and ecological notes of some ostracods from Australian inland waters. Transactions of the Royal Society of South Australia, 105, 91-138.

De Deckker, P., Bauld, J., and Burne, R.V., 1982. Pillie Lake, Eyre Peninsula, South Australia: Modern environment and biota, dolomite sedimentation, and Holocene history. Transactions of the Royal Society of South Australia, 106, 169-181.

DeHoff, R.T., and Rhines, F.N. (eds.), 1968. Quantitative Microscopy. McGraw-Hill, New York.

Delesse, M.A., 1847. Procédé mécanique pour déterminer la composition des roches. Compte Rendu des Séances de l'Académie des Sciences, Paris, 25, 544-545.

Dodson, J.R., 1974a. Vegetation and climatic history near Lake Keilambete, Western Victoria. Australian Journal of Botany, 22, 709-717.

Dodson, J.R., 1974b. Vegetation history and water fluctuations at Lake Leake, south-eastern South Australia. I. 10,000 B.P. to present. Australian Journal of Botany, 22, 719-741.

Dodson, J.R., 1975. Late Quaternary vegetation history of southeastern South Australia. Ph.D. thesis, Australian National University, Canberra.

Dodson, J.R., 1977. Late Quaternary palaeoecology of Wyrie Swamp, south-eastern South Australia. Quaternary Research, 8, 97-114.

Dodson, J.R., and Wilson, I.B., 1975. Past and present vegetation of Marshes Swamp in south-eastern South Australia. Australian Journal of Botany, 23, 123-150.

Edmonds, R.L. (ed.) 1979. Aerobiology. The Ecological Systems Approach. Dowden, Hutchinson and Ross, Stroudsburg. (US/IBP Synthesis series 10).

Eichler, Hj., 1965. Supplement to J.M. Black's Flora of South Australia. South Australian Government Printer, Adelaide.

Faegri, K., and Iversen, J., 1975. Textbook of Pollen Analysis. Hafner, New York, 3rd edition.

Flannery, T.F., and Gott, B., in press. Late Pleistocene megafaunal extinction and the Spring Creek locality of Western Victoria. Proceedings of the Linnaean Society of New South Wales, to appear.

Flinders, M., 1814. A Voyage to Terra Australis. G. and W. Nicol, London.

Forestry Department, A.N.U., Resource and Environment Consultant Group, 1973. A Resource and Management Survey of the Cotter River Catchment. Canberra.

Fredskild, B., 1967. Postglacial plant succession and climatic changes in a west Greenland bog. Review of Paleobotany and Palynology, 4, 113-127.

Friedel, R.A., Queiser, J.A., and Retcofsky, H.L., 1970. Coal-like substances from low-temperature pyrolysis at very long reaction times. Journal of Physical Chemistry., 74, 908-912.

Füchtbauer, H., 1974. Sediments and Sedimentary Rocks 1. Pt.II of W.v. Engelhardt, H. Füchtbauer and G. Müller, Sedimentary Petrology. Halstead Press, New York, 2nd edition.

Garrett-Jones, S.E., 1979. Evidence for changes in Holocene vegetation and lake sedimentation in the Markham Valley, Papua New Guinea. Ph.D. thesis, Australian National University, Canberra.

Gill, A.M., 1975. Fire and the Australian flora: a review. Australian Forestry, 38, 1-25.

Gill, A.M., 1977. Management of fire-prone vegetation for plant species conservation in Australia. Search, 8, 20-25.

Gill, A.M., 1981a. Post-settlement fire history in Victorian landscapes. In A.M. Gill, R.H. Groves and I.R. Noble (eds.), Fire and the Australian Biota, pp. 77-98. Australian Academy of Science, Canberra.

Gill, A.M., 1981b. Adaptive responses of Australian vascular plant species to fire. In A.M. Gill, R.H. Groves, and I.R. Noble (eds.), Fire and the Australian Biota, pp. 243-272. Australian Academy of Science, Canberra.

Gill, A.M., Groves, R.H., and Noble, I.R. (eds.) 1981. Fire and the Australian Biota. Australian Academy of Science, Canberra.

Glagoleff, A.A., 1933. On the geometrical methods of quantitative mineralogic analysis of rocks. Transactions of the Institute of Economic Mineralogy and Metallurgy, Moscow, 59, 475.

Goodall, D.W., 1952. Some considerations in the use of point quadrats for the analysis of vegetation. Australian Journal of Scientific Research, B, 5, 1-41.

Goodall, D.W., 1953. Point quadrat methods for the analysis of vegetation. Australian Journal of Botany, 1, 457-461.

Graf, W.H., 1971. Hydraulics of Sediment Transport. McGraw-Hill, New York.

Gray, J., 1965. Extraction techniques. In B. Kummel, and D. Raup (eds.), Handbook of Paleontological Techniques, pp. 530-587. Freeman, San Francisco.

Green, D.G., 1976. Nova Scotian forest history - evidence from statistical analysis of pollen data. Ph.D. thesis, Dalhousie University, Halifax.

Green, D.G., 1981. Time series and postglacial forest ecology. Quaternary Research, 15, 265-277.

Green, D.G., in prep. Interactive pollen time series analysis. (Submitted to Pollen et Spores).

Green, H.L., and Lane, W.R., 1964. Particulate Clouds: Dusts, Smokes and Mists. Spon, London, 2nd edition.

Gregory, K.J., and Walling, D.E., 1973. Drainage Basin Form and Process. A Geomorphological Approach. Arnold, London.

Gregory, P.H., 1973. The Microbiology of the Atmosphere. Leonard Hill, London, 2nd edition.

Hallam, S., 1975. Fire and Hearth. Australian Institute of Aboriginal Studies, Canberra.

Harris, T.M., 1958. Forest fire in the Mesozoic. Journal of Ecology, 46, 447-453.

Head, L., 1983. Environment as artefact: a geographic perspective on the Holocene occupation of southwestern Victoria. Archaeology in Oceania, to appear.

Heyligers, P.C., 1977. The Natural History of the Tasmanian, Manjimup and Eden-Bombala Woodchip Export Concession Areas. Department of Environment, Housing and Community Development, Studies Bureau Report 22, Australian Government Publishing Service, Canberra.

Hilliard, J.E., and Cahn, J.W., 1961. An evaluation of procedures in quantitative metallography for volume-fraction analysis. Transactions of the Metallurgical Society of the American Institute of Mining, Metallurgical and Petroleum Engineers, 221, 344-352.

Hooley, A.D., Southern, W., and Kershaw, A.P., 1980. Holocene vegetation and environments of Sperm Whale Head, Victoria, Australia. Journal of Biogeography, 7, 349-362.

Hope, G.S., 1974. The vegetation history from 6000 B.P. to present of Wilsons Promontory, Victoria, Australia. New Phytologist, 73, 1035-1053.

Hope, G.S., 1978. The late Pleistocene and Holocene vegetational history of Hunter Island, north-western Tasmania. Australian Journal of Botany, 26, 493-514.

Hope, G.S., 1983a. Environmental change at Telefomin, Papua New Guinea. Journal of Tropical Geography, to appear.

Hope, G.S., 1983b. Complementary pollen spectra from a surface site and swamp at Kosipe Mission, P.N.G. In P. Duerden and W. Ambrose (eds.), First Australian Conference on Archaeometry. Prehistory Department, Australian National University, Canberra.

Hope, G.S., in press. Australian environmental change: timing, directions, magnitudes and rates. In P.S. Martin and R.G. Klein (eds.), Quaternary Extinctions: a Prehistoric Revolution, pp. 1382-1400. University of Arizona Press, Tucson.

Hope, G.S., and Peterson, J.A., 1976. Palaeo-environments. In G.S. Hope, J.A. Peterson, U. Radok and I. Allison, The Equatorial Glaciers of New Guinea. A.A. Balkema, Rotterdam.

Hope, G.S., and Spriggs, M.J.T., 1982. A preliminary pollen sequence from Aneityum Island, Southern Vanuatu. Indo-Pacific Prehistory Association Bulletin, 3, 88-94.

Hope, J.H., Clark, R.L., and Hope, G.S., in prep. Palaeoecology of the Rocky River bone bed, Kangaroo Island, South Australia. (To be submitted to Alcheringa.)

Hope, J.H., Lampert, R.J., Edmondson, L., Smith, M.J., and G.F. van Tets, 1977. Late Pleistocene faunal remains from Seton Rock-shelter, Kangaroo Island, South Australia. Journal of Biogeography, 4, 363-385.

Horton, D.R., 1982. The burning question: Aborigines, fire and Australian ecosystems. Mankind, 13, 237-251.

Howitt, A.W., 1890. The eucalypts of Gippsland. Transactions of the Royal Society of Victoria, II, 83-120.

Humphreys, F.R., and Ironside, G.E., 1980. Charcoal from New South Wales species of timber. Forestry Commission of N.S.W., Research Note No.44, 3rd edition.

Hutchings, P.T., and Oswald, K.M., 1975. Litter fall and litter accumulation in eucalypt forests of the Australian Capital Territory. In Proceedings of the 3rd Australian Specialist Conference of Soil Biologists, Adelaide.

Hutchinson, G.E., and Goulden, C.E., 1966. The history of Laguna de Petenxil; the plant microfossils. Memoirs of the Connecticut Academy of Arts and Sciences, 17, 67-73.

Irani, R.R., and Callis, F.C., 1963. Particle Size: Measurement, Interpretation, and Application. Wiley, New York.

Iversen, J., 1941. Land occupation in Denmark's Stone Age. Danmarks Geologiske Undersøgelse., II(66), 68pp.

Iversen, J., 1952. Origin of the flora of western Greenland in the light of pollen analysis. Oikos, 4, 85-103.

Iversen, J., 1964. Retrogressive vegetational succession in the post-glacial. Journal of Ecology, supp. 52, 59-70.

Iversen, J., 1969. Retrogressive development of a forest ecosystem demonstrated by pollen diagrams from fossil mor. Oikos, supp. 12, 35-49.

Jackson, W.D., 1965. Vegetation. In J.L. Davies (ed.), Atlas of Tasmania, pp. 30-35. Lands and Surveys Department, Hobart.

Jackson, W.D., 1968. Fire, air, water and earth - an elemental ecology of Tasmania. Proceedings of the Ecological Society of Australia, 3, 9-16.

Janssen, C.R., 1966. Recent pollen spectra from the deciduous and coniferous-deciduous forests of north-eastern Minnesota: a study in pollen dispersal. Ecology, 47, 804-825.

Janssen, C.R., 1973. Local and regional pollen deposition. In H.J.B. Birks and R.G. West (eds.), Quaternary Plant Ecology, pp. 31-42. Blackwell, Oxford.

Jones, R., 1968. The geographical background to the arrival of man in Australia and Tasmania. Archaeology and Physical Anthropology in Oceania, 3, 186-215.

Jones, R., 1969. Fire-stick farming. Australian Natural History, 16, 224-228.

Jones, R., 1975. The Neolithic, Palaeolithic and the hunting gardeners: Man and land in the Antipodes. In R.P. Suggate and M.M. Cresswell (eds.), Quaternary Studies, pp. 21-34. Royal Society of New Zealand, Wellington.

Jones, R., 1977. Man as an element of a continental fauna: the case of the sundering of the Bassian bridge. In J. Allen, J. Golson and R. Jones (eds.), Sunda and Sahul. Prehistoric Studies in Southeast Asia, Melanesia and Australia, pp. 317-386. Academic Press, London.

Jones, R., 1979. The fifth continent: problems concerning the human colonization of Australia. Annual Review of Anthropology, 8, 445-466.

Jones, R., 1980. Cleaning the country: the Gidjingali and their Arnhemland environment. BHP Journal, 1.80, 10-15.

Jowsey, P.C., 1966. An improved peat sampler. New Phytologist, 65, 245-248.

Kemp, E.M., 1978. Tertiary climatic evolution and vegetation history in the southeast Indian Ocean region. Palaeogeography, Palaeoclimatology, Palaeoecology, 24, 169-208.

Kemp, E.M., 1981. Pre-Quaternary fire in Australia. In A.M. Gill, R.H. Groves, and I.R. Noble (eds.), Fire and the Australian Biota, pp. 3-21. Australian Academy of Science, Canberra.

Kershaw, A.P., 1970. Pollen morphological variation within the Casuarinaceae. Pollen et Spores, 12, 145-161.

Kershaw, A.P., 1976. A Late Pleistocene and Holocene pollen diagram from Lynch's Crater, north-eastern Queensland, Australia. New Phytologist, 77, 469-498.

Kershaw, A.P., 1978. Record of last interglacial-glacial cycle from north-eastern Queensland. Nature, 272, 159-161.

Kershaw, A.P., 1981. Quaternary vegetation and environments. In A. Keast (ed.), Ecological Biogeography of Australia, pp. 81-101. Junk, The Hague.

Ladd, P.G., 1978. Vegetation history at Lake Curlip in lowland eastern Victoria, from 5200 BP to present. Australian Journal of Botany, 26, 393-414.

Ladd, P.G., 1979. A Holocene vegetation record from the eastern side of Wilson's Promontory, Victoria. New Phytologist, 82, 265-276.

Lampert, R.J., 1979. Aborigines. In M.J. Tyler, C.R. Twidale and J.K. Ling (eds.), Natural History of Kangaroo Island, pp. 81-89. Royal Society of South Australia, Adelaide.

Lampert, R.J., 1981. The great Kartan mystery. Terra Australis, 5, 210pp.

Lange, R.T., 1979. Native vegetation. In M.J. Tyler, C.R. Twidale and J.K. Ling (eds.), Natural History of Kangaroo Island, pp. 65-80. Royal Society of South Australia, Adelaide.

Laut, P., Heyligers, P.C., Keig, G., Löffler, E., Margules, C., Scott, R.M., and M.E. Sullivan, 1977. Environments of South Australia. CSIRO Division of Land Use Research, Canberra.

Leopold, L.B., Wolman, M.G., and Miller, J.P., 1964. Fluvial Processes in Geomorphology. Freeman, San Francisco.

Levy, E.B., and Madden, E.A., 1933. The point method of pasture analysis. New Zealand Journal of Agriculture, 46, 267-279.

Livingstone, D.A., and Clayton, W.D., 1980. An altitudinal cline in tropical African grass floras and its paleoecological significance. Quaternary Research, 13, 392-402.

Luke, R.H., and McArthur, A.G., 1978. Bushfires in Australia. Australian Government Publishing Service, Canberra.

McArthur, A.G., 1972. Fire control in the arid and semi-arid lands of Australia. In The Use of Trees and Shrubs in the Dry Country of Australia, pp. 488-515. Australian Government Publishing Service, Canberra.

MacArthur, D.A., 1966. Particle sizes in bushfire smoke. Australian Forestry, 30, 274-278.

McBryde, I., and Nicholson, P.H., 1978. Aboriginal man and the land in south-western Australia. Studies in Western Australian History, 3, 38-42.

McIntyre, G.A., 1952. A method for unbiased selective sampling, using ranked sets. Australian Journal of Agricultural Research, 3, 385-390.

Mackay, S.M., and Cornish, P.M., 1982. Effects of wildfire and logging on the hydrology of small catchments near Eden, N.S.W. In E.M. O'Loughlin and L.J. Bren (eds.), The First National Symposium on Forest Hydrology, pp. 111-117. Institution of Engineers, Australia, publication No. 82/6.

Macphail, M.K., 1980. Regeneration processes in Tasmanian forests. Search, 11, 184-190.

Martin, H.A., 1978. Evolution of the Australian flora and vegetation through the Tertiary: evidence from pollen. Alcheringa, 2, 181-202.

Mehringer, P.J., Arno, S.F., and K.L. Peterson, 1977. Postglacial history of Lost Trail Pass Bog, Bitterroot Mountains, Montana. Arctic and Alpine Research, 9, 345-368.

Merkt, J., 1971. Zuverlässige Auszählungen von Jahresschichten in Sedimenten mit Hilfe von Gross-Dünnschliffen. Archiv für Hydrobiologie, 69, 145-154.

Miles, R.E., and Davy, P.J., 1976. Precise and general conditions for the validity of a comprehensive set of stereological fundamental formulae. Journal of Microscopy, 107, 211-226.

Mooney, H.A., and Conrad, C.E., (eds.) 1977. Proceedings of the Symposium on the Environmental Consequences of Fire and Fuel Management in Mediterranean Ecosystems. USDA Forest Service, Washington, General Technical Report WO-3.

Murray, P.F., Goede, A., and Bada, J.L., 1980. Pleistocene human occupation at Beginners Luck Cave, Florentine Valley, Tasmania. Archaeology and Physical Anthropology in Oceania, 15, 142-152.

Nicholson, P.H., 1981. Fire and the Australian Aborigine - an enigma. In A.M. Gill, R.H. Groves and I.R. Noble (eds.), Fire and the Australian Biota, pp. 55-76. Australian Academy of Science, Canberra.

Nicholson, W.L., 1978. Application of statistical methods in quantitative microscopy. Journal of Microscopy, 113, 223-239.

Noble, I.R., and Slatyer, R.O., 1981. Concepts and models of succession in vascular plant communities subject to recurrent fire. In A.M. Gill, R.H. Groves and I.R. Noble (eds.), Fire and the Australian Biota, pp. 311-335. Australian Academy of Science, Canberra.

Ogden, E.C., Raynor, G.S., Hayes, J.V., Lewis, D.M., and J.H. Haines, 1974. Manual for Sampling Airborne Pollen. Hafner, New York.

Oldfield, F., 1970. Some aspects of scale and complexity in pollen-analytically based palaeoecology. Pollen et Spores, 12, 163-171.

Olive, L.J., Rieger, W.A., and Burgess, J.S., 1978. Assessment of the hydrologic influences of clearfelling in the Eden area, N.S.W.: methodology and pre-treatment calibration. Paper presented at the Institute of Australian Geographers' 15th Annual Conference, Townsville.

O'Loughlin, E.M., Cheney, N.P., and Burns, J., 1982. The Bushrangers experiment: hydrological response of a eucalypt catchment to fire. In E.M. O'Loughlin and L.J. Bren (eds.), The First National Symposium on Forest Hydrology, pp. 132-138. Institution of Engineers, Australia, National Conference Publication No. 82/6.

Olson, J.S., 1963. Energy storage and the balance of producers and decomposers in ecological systems. Ecology, 44, 322-331.

Parkin, L.W. (ed.), 1969. Handbook of South Australian Geology. Geological Survey of South Australia, Adelaide.

Pasquill, F., 1974. Atmospheric Diffusion. Ellis Horword, Chichester, 2nd edition.

Patterson, W.A., unpublished. Charcoal as a fossil indicator of fire.

Peck, R.M., 1974. Pollen budget studies in a small Yorkshire catchment. In H.J.B. Birks and R.G. West (eds.), Quaternary Plant Ecology, pp. 43-61. Halsted Press, New York.

Péron, F., and Freycinet, L., 1807-16. Voyage de Découvertes aux Terres Australes. L'Imprimerie impériale, Paris.

Pettijohn, F.J., 1957. Sedimentary Rocks. Harper, New York, 2nd edition.

Polach, H., and Singh, G., 1980. Contemporary ^{14}C levels and their significance to sedimentary history of Bega Swamp, New South Wales. Radiocarbon, 22, 398-409.

Purdie, R.W., and Slatyer, R.O., 1976. Vegetation succession after fire in sclerophyll woodland communities in south-eastern Australia. Australian Journal of Ecology, 1, 223-236.

Rieger, W.A., Olive, L.J., and Burgess, J.S., 1979. Sediment discharge response to clear-fell logging in selected small catchments, Eden NSW. In Proceedings of the 10th New Zealand Geography Conference, pp. 44-48.

Rieger, W.A., Olive, L.J., and Burgess, J.S., 1982. The behaviour of sediment concentrations and solute concentrations in small forested catchments. In E.M. O'Loughlin and L.J. Bren (eds.), The First National Symposium on Forest Hydrology, pp. 79-83. Institution of Engineers, Australia, National Conference Publication No. 82/6.

Ritchie, J.C., and Lichti-Federovich, 1967. Pollen dispersal phenomena in arctic-subarctic Canada. Review of Palaeobotany and Palynology, 3, 255-266.

Ross, D.G., Knight, I., Packham, D.R., and R.G. Vines, 1980. Mathematical Smoke Dispersion Model: Prescribed Burns. Mathematics Department, Caulfield Institute of Technology, Melbourne.

Rymer, L., and Neale, J., 1981. Freeze coring as a method of collecting unconsolidated lake sediments. Australian Journal of Ecology, 6, 123-126.

Saarnisto, M., Huttunen, P., and Tolonen, K., 1977. Annual lamination of sediments in Lake Lovojärvi, southern Finland, during the past 600 years. Annales Botanici Fennici, 14, 35-45.

Sarnthein, M., and Koopmann, B., 1980. Late Quaternary deep-sea record on Northwest African dust supply and wind circulation. In M. Sarnthein, E. Seibold and P. Rognon (eds.), Sahara and Surrounding Seas, pp. 239-253. Vol. 12 of Palaeoecology of Africa. A.A. Balkema, Rotterdam.

Sauer, C.O., 1956. The agency of Man on the earth. In W.L. Thomas (ed.), Man's Role in Changing the Face of the Earth, Vol.1, pp. 49-69. University of Chicago Press, Chicago.

Schaefer, V.J., 1974. Some physical relationships of fine particle smoke. In Proceedings of the Annual Tall Timbers Fire Ecology Conference Number 13, pp. 283-294. Tall Timbers Research Station, Tallahassee.

Schütz, L., 1979. Sahara dust transport over the North Atlantic Ocean-model calculations and measurements. In C. Morales (ed.), Saharan Dust, pp. 267-277. SCOPE report 14, Wiley, Chichester.

Schütz, L., and Jaenicke, R., 1974. Particle number and mass distributions above 10^{-4}cm radius in sand and aerosol of the Sahara desert. Journal of Applied Meteorology, 13, 863-870.

Shneour, E.A., 1966. Oxidation of graphitic carbon in certain soils. Science, 151, 991-992.

Simola, H., 1977. Diatom succession in the formation of annually laminated sediment in Lovojärvi, a small eutrophicated lake. Annales Botanici Fennici, 14, 143-148.

Singh, G., 1981a. Late Quaternary pollen records and seasonal palaeoclimates of Lake Frome, South Australia. Hydrobiologia, 82, 419-430.

Singh, G., 1981b. Environmental upheaval: vegetation of Australasia during the Quaternary. In J.M.B. Smith (ed.), A History of Australasian Vegetation, pp. 90-108. McGraw-Hill, Sydney.

Singh, G., Kershaw, A.P., and Clark, R.L., 1981. Quaternary vegetation and fire history in Australia. In A.M. Gill, R.H. Groves and I.R. Noble (eds.), Fire and the Australian Biota, pp. 23-54. Australian Academy of Science, Canberra.

Singh, G., Opdyke, N.D., and Bowler, J.M., 1981. Late Cainozoic stratigraphy, palaeomagnetic chronology and vegetational history from Lake George, N.S.W. Journal of the Geological Society of Australia, 28, 435-452.

Smith, A.G., 1970. The influence of Mesolithic and Neolithic man on British vegetation: a discussion. In D. Walker and R.G. West (eds.), Studies in the Vegetational History of the British Isles, pp. 81-96. Cambridge University Press.

Smith, D.M., Griffin, J.J., and Goldberg, E.D., 1973. Elemental carbon in marine sediments: a baseline for burning. Nature, 241, 268-270.

Solomon, A.M., Blasing, T.J., and Solomon, J.A., 1982. Interpretation of floodplain pollen in alluvial sediments from an arid region. Quaternary Research, 18, 52-71.

Solomon, W.R., Burge, H.A., and Boise, J.R., 1980. Performance of adhesives for rotating-arm impactors. Journal of Allergy and Clinical Immunology, 65, 467-470.

Specht, R.L., 1966. The growth and distribution of mallee-broombush (Eucalyptus incrassata - Melaleuca uncinata association) and heath vegetation near Dark Island Soak, Ninety-Mile Plain, South Australia. Australian Journal of Botany, 14, 361-371.

Specht, R.L., 1970. Vegetation. In G.W. Leeper (ed.), The Australian Environment, pp. 44-67. CSIRO and Melbourne University Press, Melbourne, 4th edition.

Specht, R.L., 1972. The Vegetation of South Australia. South Australian Government Printer, Adelaide, 2nd edition.

Staplin, F.L., 1969. Sedimentary organic matter, organic metamorphism, and oil and gas occurrence. Bulletin of Canadian Petroleum Geology, No.17, pp. 47-66.

Starling, R.N., and Crowder, A., 1981. Pollen in the Salmon River system, Ontario, Canada. Review of Palaeobotany and Palynology, 31, 311-334.

Stewart, O.C., 1956. Fire as the first great force employed by Man. In W.L. Thomas (ed.), Man's Role in Changing the Face of the Earth, Vol.1, pp. 115-133. University of Chicago Press, Chicago.

Stockmarr, J., 1972. Tablets with spores used in absolute pollen analysis. Pollen et Spores, 13, 615-621.

Stockton, J., 1982. Fires by the seaside: historic vegetation changes in northwestern Tasmania. Papers and Proceedings of the Royal Society of Tasmania, 116, 53-66.

Swain, A.M., 1973. A history of fire and vegetation in Northeastern Minnesota as recorded in lake sediments. Quaternary Research, 3, 383-396.

Swain, A.M., 1978. Environmental change during the past 2000 years in North Central Wisconsin: analysis of pollen, charcoal and seeds from varved lake sediments. Quaternary Research, 10, 55-68.

Tauber, H., 1965. Differential pollen dispersal and the interpretation of pollen diagrams. Geological Survey of Denmark, Ser. II, No.89.

Tauber, H., 1967. Investigations of the mode of pollen transfer in forested areas. Review of Palaeobotany and Palynology, 3, 277-286.

Tauber, H., 1974. A static non-overload pollen collector. New Phytologist, 73, 359-369.

Teichmüller, M., 1975. Origin of the petrographic constituents of coal. In E. Stach, M.-Th. Mackowsky, M. Teichmüller, G.H. Taylor, D. Chandra and R. Teichmüller, Stach's Textbook of Coal Petrology, English Translation pp. 167-237. Gebrüder Borntraeger, Berlin.

Terasmae, J., and Weeks, N.C., 1979. Natural fires as an index of paleoclimate. Canadian Field-Naturalist, 93, 116-125.

Thom, B.G., and Chappell, J., 1975. Holocene sea levels relative to Australia. Search, 6, 90-93.

Thom, B.G., and Wasson, R.J. (Conveners) 1982. Holocene Research in Australia 1978-1982. Department of Geography, Royal Military College, Duntroon.

Thorne, A.G., 1980. The longest link: human evolution in Southeast Asia and the settlement of Australia. In J.J. Fox, R.G. Garnaut, P.T. McCawley and J.A.C. Mackie (eds.), Indonesia: Australian Perspectives, pp. 35-43. Research School of Pacific Studies, Australian National University, Canberra.

Tindale, N.B., 1959. Ecology of primitive Aboriginal Man in Australia. In A. Keast, R.L. Crocker and C.S. Christian (eds.), Biogeography and Ecology in Australia, pp. 36-51. Monographiae Biologicae 8, Junk, The Hague.

Tindale, N.B., Fenner, F.J., and Hall, F.J., 1935. Mammal bone beds of probable Pleistocene age, Rocky River, Kangaroo Island. Transactions of the Royal Society of South Australia, 59, 103-106.

Tippett, R., 1964. An investigation into the nature of the layering of deep-water sediments in two eastern Ontario lakes. Canadian Journal of Botany, 42, 1693-1709.

Tolonen, K., in press. The postglacial fire record. In R.W. Wein and D.A. MacLean (eds.), Fire in Northern Circumpolar Ecosystems. Wiley, Chichester.

Tolonen, M., 1978. Palaeoecology of annually laminated sediments in Lake Ahvenainen, S. Finland. I. Pollen and charcoal analyses and their relation to human impact. Annales Botanici Fennici, 15, 177-208.

Tsukada, M., and Deevey, E.S., 1967. Pollen analyses from four lakes in the Southern Maya area of Guatemala and El Salvador. In E.J. Cushing and H.E. Wright (eds.), Quaternary Paleoecology, pp. 303-331. Yale University Press, New Haven.

Turner, D.B., 1980. Atmospheric dispersion modeling: a critical review. In H.M. Englund and W.T. Beery (eds.), Atmospheric Dispersion Modeling, pp. 2-19. Air Pollution Control Association Reprint Series, ACPA, Pittsburgh.

Underwood, E.E., 1970. Quantitative Stereology. Addison-Wesley, Reading, Mass.

United States Department of Agriculture Forest Service, 1976. Southern Forestry Smoke Management Guidebook. Southeastern Forest Experiment Station, Asheville.

Van Loon, A.P., 1977. Bushland Fuel Quantities in the Blue Mountains-Litter and Understorey. Forestry Commission of N.S.W. Research Note No. 33, Sydney.

Vanoni, V.A. (ed.), 1975. Sedimentation Engineering. American Sociey of Civil Engineers, New York.

Van Wagner, C.E., 1968. The line intersect method in forest fuel sampling. Forest Science, 14, 20-26.

Vines, R.G., 1977. Fire's effect on the atmosphere. In H.A. Mooney and C.E. Conrad (eds.), Proceedings of the Symposium on the Environmental Consequences oF Fire and Fuel Management in Mediterranean Ecosystems, pp. 142-145. USDA Forest Service General Technical Report WO-3, Washington.

Vines, R.G., Gibson, L., Hatch, A.B., King, N.K., MacArthur, D.A., Packham, D.R., and R.J. Taylor, 1971. On the Nature, Properties and Behaviour of Bushfire Smoke. CSIRO Division of Applied Chemistry Technical Paper No. 1, Melbourne.

Waddington, J.C.B., 1969. A stratigraphic record of the pollen influx to a lake in the Big Woods of Minnesota. Geological Society of America Special Paper 123, 263-282.

Wakefield, N.A., 1970. Bushfire frequency and vegetational change in south-eastern Australian forests. Victorian Naturalist, 87, 152-157.

Walker, D., 1970. Direction and rate in some British Post-glacial hydroseres. In D. Walker and R.G. West (eds.), Studies in the Vegetational History of the British Isles, pp. 117-139. Cambridge University Press.

Walker, D., 1982. Vegetation's fourth dimension. New Phytologist, 90, 419-429.

Walker, D., and Singh, G., 1981. Vegetation history. In R.H. Groves (ed.), Australian Vegetation, pp. 26-43. Cambridge University Press.

Walker, G.P.L., 1971. Grain-size characteristics of pyroclastic deposits. Journal of Geology, 79, 696-714.

Walker, J., 1979. Aspects of Fuel Dynamics in Australia. CSIRO Division of Land Use Research Technical Memorandum 79/7, Canberra.

Walker, J., 1981. Fuel dynamics in Australian vegetation. In A.M. Gill, R.H. Groves, and I.R. Noble (eds.), Fire and the Australian Biota, pp. 101-127. Australian Academy of Science, Canberra.

Weibel, E.R., 1973. Stereological techniques for electron microscopic morphometry. In M.A. Hayat (ed.), Principles and Techniques of Electron Microscopy; Biological Applications, Vol.3, pp. 237-296. Van Nostrand Reinhold, New York.

Weibel, E.R., 1979. Practical Methods for Biological Morphometry. Vol.1 of Stereological Methods, Academic Press, London.

Weibel, E.R., 1980. Theoretical Methods. Vol.2 of Stereological Methods, Academic Press, London.

White, J.P., and O'Connell, J.F., 1979. Australian prehistory: new aspects of antiquity. Science, 203, 21-28.

Willis, J.H., 1970-1972. A Handbook to Plants in Victoria. Melbourne University Press, Melbourne, 2 volumes.

Wilson, S.R., and Ward, G.K., 1981. Evaluation and clustering of radiocarbon age determinations: procedures and paradigms. Archaeometry, 23, 19-39.

Wright, H.E., 1980. Cores of soft lake sediments. Boreas, 9, 107-114.

Appendix A

POINT COUNT PROCEDURE

The procedure recommended for point count estimates of the area of charcoal in pollen preparations is detailed below, with a worked example using data obtained from Figure A.1.

Procedure	Example
1. Count 1 or more transects.	Count transects numbered 1-4.
2. Calculate first estimate of P: $P = C/N$.	$C = 7$, $N = 80$. $P = 7/80 = 0.09$.
3. Select relative error.	Say, $\pm$ 10%; $(s_p/P) = 0.10$.
4. Calculate necessary N for given relative error: $N = (1-P)/P(s_p/P)^2$, or estimate from Figure 3.2.	$N = (1-0.09)/0.09(0.10)^2 = 1011$. From Figure 3.2, for $100P = 9$, *ca.* 1010 points are required for a relative standard deviation of $\pm$ 10%, 4000 points for $\pm$ 5% and *ca.* 165 points for $\pm$ 25%.
5. Count to N or as many points as possible.	400 points have been applied.
6. Calculate $P = C/N$.	$P = 41/400 = 0.103$.
7. Estimate area of charcoal on slide: $A = P.A_p$.	$A_p = 100cm^2$ $A = 0.103 \times 100 = 10.3cm^2$.
8. Calculate standard deviation of A: $s_A = A_p \sqrt{P(1-P)/N}$.	$s_A = 100 \sqrt{0.103(1-0.103)/400}$ $= 1.52\ cm^2$.
9. If required, calculate relative error: s_A/A, or 95% confidence limits: $A \pm 2s_A$.	$s_A/A = 0.15$, *i.e.*, $\pm$ 15%. 95% confidence limits lie at 10.3 ± 3.04, *i.e.*, $7.26cm^2$ and $13.34cm^2$.
10. Estimate area of charcoal in unit volume of sediment: for known volume of sample, $A_c = A.V_s/V_p.V$; if marker grains are used, $A_c = A.M/M_p.V$.	If Figure A.1 has been magnified from a sample area (A_p) on a microscope slide of $10cm^2$, then the estimated area (A) of charcoal on that slide would be $1.03cm^2$. If $V_p = 0.06cm^3$, $V_s = 0.7cm^3$ and $V = 2.5\ cm^3$: $A_c = (1.03 \times 0.7)/(0.06 \times 2.5)$ $= 4.81\ cm^2/cm^3$. If marker grains were used, with $M = 12,500$ and $M_p = 1070$, then: $A_c = (1.03 \times 12,500)/(1070 \times 2.5)$ $= 4.81\ cm^2/cm^3$.
11. Estimate mean annual influx of charcoal: $A_i = A_c/T$.	If $T = 8$ years, then: $A_i = 4.81/8$ $= 0.60\ cm^2/cm^2/year$.

<u>Symbols used are:</u>

A = estimated area of charcoal on slide

A_c = estimated area of charcoal in unit volume of sediment

A_i = estimated annual influx of charcoal to sediment

A_p = area of sample on slide

C = number of points falling on charcoal

M = number of marker grains or spheres added to original sediment sample

M_p = number of marker grains or spheres on slide

N = total number of points applied

P = estimated probability of a random point falling on charcoal

s_A = standard deviation of A

s_P = standard deviation of P

T = number of years in original sediment sample

V = volume of original sediment sample

V_p = volume of preparation on slide

V_s = volume of pollen preparation

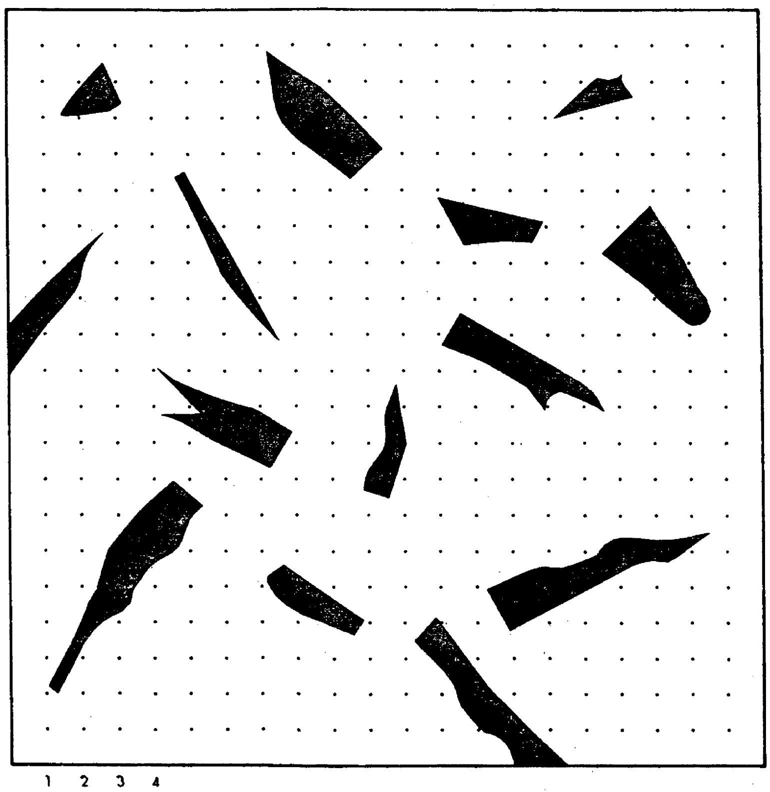


Figure A.1. An example constructed to illustrate point count estimation of area. Black card one tenth of the outlined area was cut and the pieces distributed over the grid of 400 points.

Appendix B

POLLEN COUNTS

Listed below are complete counts of all pollen taxa in all samples used in the analyses summarized in Chapter 7. Taxa are in alphabetical order and samples in order of depth. Full names of taxa corresponding to the column headings are listed after the raw data from all sites.

POLLEN COUNTS

1. Lashmar's Lagoon cores (Chapter 7.1)

(a) Core LL10

Depth cm	ACAC	ACAE	ADEN	AMYE	APIA	ASTL	ASTT	BANK	BEYE	BURS	CALY	CARY	CASO
0	4						19						22
10	7					2	19			1			27
30	5						48						17
50	11						40						21
70	6		1				35						40
90	3						19				1		23
110	11						28						26
130	2						23						20
150	5						14						15
170	3						6						8
190	3		1				17				1		11
210	4						12				1		22
230	2						8						9
250	3						17						12
270	2						15						11
290	5						10						7
310	3						13			1	1		23
330							12				1		7
350	1				13		9			2			13
370	8				10		15						10
390	8				5		8			1			11
410	4				5		18						10
430	9				1		10						5
450	14	1		1			12			1	2		9

Depth cm	CASS	CHEN	CORR	CYPS	DODO	DROS	EPAC	EUCA	EUPH	EXOC	GOOD	GREV	GYRO
0	1	12		2	3		1	14			3		
10	2	11		1	2			10			4		1
30	6	9		1				18					1
50	6	19			1			16					
70	8	11						22			1		2
90	18	17			5			32			6		1
110	9	14			3			25					2
130	5	20			4			35			2		1
150	13	23			1			26					1
170	15	31			9			30					1
190	23	28			1			21					
210	23	23			2			24					
230	18	35			3	1		35					
250	17	11		1	4			32					3
270	16	9		1	6			16			2		
290	15	18			2			26			3		1
310	8	22			5		1	26					1
330	19	26		2	3			27			4		2
350	16	13		5	6			20			5		5
370	28	11		7	7			18			4		3
390	19	24		2	3			20			4		
410	12	14		5	4			18			6		
430	5	9		3	9			26			3	1	3
450	19	12		5	10			21			2	1	

Depth cm	HALO	KUNZ	LEPT	LILI	MELA	MELH	MICR	MUEH	MYEL	MYMU	MYOP	OPER	OTTE
0	9		8	1		27	1		8	9			1
10	15		11			30	2		6	6			
30	20		11		3	24			31	5			
50	4		6	2	1	16		5	138	6		2	
70	6		3	4	3	22							
90	1		2	2	2	20		3					
110	11		2	1	6	18		2				1	
130	1		4	3	1	28		2	1				
150	2		10		10	28		3	3	1	1		
170			7	1	6	31		1			1		
190	3		6	2	13	27			1	1			
210	5		2	1	11	21		2			1		
230	3			1	12	27		2				1	
250	7		3	4	17	26		2	1	2		3	
270	1		12		5	54		3	5				
290	7		9		15	29		6	1	1		1	
310	8		9		13	26		3	3				
330	5		8		20	18		2	2	5			
350	2		8		13	31		2	109	75		1	
370	5		7		16	11		9	206	50			
390	6		8	2	7	17		11	85	11	1	1	
410	7		7	5	10	24		8	117	33		3	
430	9		5	4	8	19		21	55	10		4	
450	1	1	1		20	14		6	41	24		2	

Depth cm	PLAN	POAS	PODO	POLY	POMA	PORT	RANU	REST	RUTA	SPBR	SPFE	THRY	UNID
0		29					1	4			1	1	2
10		19					1	1				2	4
30		1										1	9
50		6											1
70		4											3
90													
110		2					3						3
130											1		7
150		2											2
170		2											3
190											1		2
210		1						1					4
230		2											2
250							1						2
270								1					4
290		3	1							1	1		4
310													4
330		1											9
350	2	3											2
370		2					1						4
390		3			1		1				1		2
410		2									1		4
430		1			1		1			1			4
450		4											2

(b) Core LL15

Depth cm	ACAC	ACAE	ADEN	AMYE	APIA	ASTL	ASTT	BANK	BEYE	BURS	CALY	CARY	CASO
430	9				4		19				2		7
450	15				1		11				1		3
470	19						9						6
490	12				1		9						15
510	8						10						14
530	6						13		1				16
550	9						5						7
570						1	12			14		1	6
590	11						10						8
610	6						8	1					13
630	15						4			3		1	16
650	13						7			2		1	9
670	22						18			2			15
675	27						5	2		4	19		9
690	1						9	2			4	1	11
710	2					1	7	6			3		10
730	4				2		9				2		13
750	3				1		7	2					16
770	2						2						19
790	2						1	1			4		13
810	3				1		9	1			2		11
830	3						7			1	2		14
850	2						5	2		2			14
870	5					1	6	1			1		8
890	2	1					3	3			6		17
910	5						4	1		1	1		17
930	1						4	2					11
950	4					1	7	2		3	2		11
970	3				1		10	2		1			15
990	3				2		7			3			7
1010	3				1		14	3		2	3		10
1030	3				1		6	6		2	3		9
1050	7				1		12			3	1		6
1070	5					1	11	2		5	2		2
1090	3				1		7	2		8	2	2	8
1110	10			1	1	2	26	2		2	3	1	15
1130	4			1	1		14	3		1			15
1150	1				1	2	22	4		1			19
1170	5				1	2	13	2				2	23
1185	5					2	19	3					22

Depth cm	CASS	CHEN	CORR	CYPS	DODO	DROS	EPAC	EUCA	EUPH	EXOC	GOOD	GREV	GYRO
430	5	12		9	3			46					
450	12	12		15	14			33					1
470	13	9		9	1			37			1		
490	26	9		6	6			42			1		
510	6	17		3	7			50			1		
530	6	7		11	6			31			2		1
550	6	44			7			16			1		
570	13	31			7			22					
590	8	26		2	5			20		1			
610	11	23			6			22					
630	7	27		4	2			18					
650	32	2		2				19					
670	16	6	1	1	2			16					
675	24	6		14				8					
690	68	10		5	1			7	2		1		
710	64	18		8				3					
730	71	15		4	1			1					
750	69	11		1	2			3					
770	91	6		5	1			2			1		1
790	71	14		3	2			6					
810	90	12		11	1			5					2
830	60	15		3				3					3
850	54	16		1	2			1					1
870	62	20		7	1			4					
890	55	13		3	1			7					1
910	43	19		1	3			2					
930	102	13		1				4					1
950	63	16		5	1			4					
970	179	21		5				4					1
990	105	24		2	3			8					2
1010	64	22		5				7					
1030	61	29		10				6					2
1050	45	46		4	1			4					
1070	39	45		12	2			3					
1090	47	39		3	1			7					1
1110	14	35		5	2			6					
1130	21	57		7	2			1					
1150	14	60		8				3					
1170	27	55		16				1					1
1185	23	38		17	2			2					

Depth cm	HALO	KUNZ	LEPT	LILI	MELA	MELH	MICR	MUEH	MYEL	MYMU	MYOP	OPER	OTTE
430	8		14		12	22			79	16			
450	5		8		5	16			42	22			
470	2		13		1	16	2		28	3	1	1	
490	4		8	1	1	26	1		24	43		1	
510			11	1	1	16			23	23		1	
530	4		26			23			11	14		2	
550	5		19		1	34		1	1			1	
570	3		15			32			1				
590	3		17			46		1					
610	3		16			45			1				
630	1		17			41							
650	3		13	1		51							
670			14	7		30			7				
675	2		17		1	20			1				
690	3		12		1	18						1	
710	4		4		1	21		2					
730	8		2			20							
750	2		8			26		1			1		
770	5		6			30			3		1	1	
790	3		6			24							
810	7		8	2		13					1		
830	5		6			25							
850	1		7		2	27					1		
870	6		7			22							
890	3		3			26							
910	5		8			36							
930	8		9			30					2		
950	3		10			17					1		
970	9		5		1	3		2	3				
990	3		9			5			3		5		
1010	1		13			6					1		
1030	5		14			4					1		
1050	6		11			1							
1070	6		18								3		
1090	4		14						1		1		
1110	11		16								2		
1130	6		11		3						1		
1150	8		8										
1170	7		13						1				
1185	8		10			1					2		

Depth cm	PLAN	POAS	PODO	POLY	POMA	PORT	RANU	REST	RUTA	SPBR	SPFE	THRY	UNID
430		2		6					2		1		6
450		4		13					1				4
470		1		13	2	1							3
490		2		7	1				2				1
510	1	5		5									4
530		6		3									4
550		2		2					1				4
570	1	3		2				1					3
590		3							1				3
610		1		1									3
630		3								1			5
650		1							2				2
670		4						2		1			7
675		5						1	1	2	2		4
690		15		1				3		1	1		2
710		13						1		8	1		2
730		16			1			1		2	1		3
750		15								1			2
770	1	14		2	1	1		1	1	1			1
790	1	14		2		1		1		1			4
810	2	20								1	6		1
830	1	19			1					3	6		3
850		14						1		1	4		6
870		18		1				2		5	6		6
890		13		1	1					1	3		1
910		9			1				1	5	1		3
930		12			1					2	1		1
950		17								5			1
970		18								6			3
990		14							1	1	1		2
1010	1	17				1				1	1		1
1030		5								1			4
1050		16							2	6	3		3
1070		17		1						3	1		3
1090	1	15		2						3	1		1
1110		18			1					6			1
1130		23							1	3	1		1
1150		20			1			1		6	2		2
1170	1	11			1					11	4		4
1185		22		2						9			3

2. Rocky River (Chapter 7.2)

(a) Black Creek swamp core

Depth cm	ACAC	APIA	ASTL	ASTT	BANK	CHEN	CYPS	EUCA	HALO
0	9	14	3	42		2	148	43	4
33	6	9		15		31	119	41	2
63	6	16	2	12		4	5	69	5
70	4			2		1	1	5	2
80			2	1	1	2	2	4	2
90	3	1	1	6		2	8	39	3
100	16	25	1	15			173	29	6
106	3	5	1	9		3	3	76	11
120	9	1		25	3	10	11	20	12
130	6			35	1	7	4	31	15
140	1			29	3	10	1	25	26
150	14			23	3	4	18	22	27
160	13			18	3	8	5	14	36
170	8			23		5	12	26	32
180	1			1		5	4		1
190				6	1	4	1	4	43
200				1				1	
210	1			8		1	1	4	11
220									
230				1				1	

Depth cm	LEPT	MELS	MYEL	MYRT	PETR	PLAN	POAS	TRIG	UNID
0	6	6		2			13		16
33	14	16		8			19		12
63	16	15		3			5		6
70	1			12			1		5
80	2			8					2
90	5			31			1		11
100	7	4		11			12	93	30
106	14	19	7	11			13		6
120	31	6	14	12		1	8		27
130	18	9	10	15		1	8		22
140	55		21	8		1	8		14
150	13	20	6	19			6		28
160	63		82	7			18		14
170	8	9	147	31		1	8		34
180			1	1	3	2	1		5
190	1		21	3			11		
200			2				1		
210	8		23		2		17		11
220									4
230						1			

(b) Bone bed trench samples

Depth cm	ACAC	APIA	ASTL	ASTT	BANK	CHEN	CYPS	EUCA	HALO
20	2		3	45		17	3	7	
25	1			36		9		6	2
40	1		1	58		1		10	
50				24				2	
60				1					
70									
80									
90				1					

Depth cm	LEPT	MELS	MYEL	MYRT	PETR	PLAN	POAS	TRIG	UNID
20	9	20		26			5		16
25	9	1		30	1		1		8
40	10	12		30	7		1		19
50		1		8					1
60									
70									
80									
90									

3. Little Swamp core (Chapter 7.3)

Depth cm	ACAC	ADRI	APIA	ASTT	BRAS	CALY	CASO	CASS	CHEN	COPR	CRYP	CYPS	DODO
5	6			20	1		9	52	10	2		36	5
15	5			18	1	1	22	125	19	1		68	3
35	3			14			30	158	15	7		47	5
60	1	2		22			76	143	15	2	4	82	4
85	5		1	14			34	165	11	8	1	25	2
100	5		2	12			43	193	15	7		30	5
120	7		1	6			24	130	10	6		11	6
137	6		1	8			16	98	11	1		13	4

Depth cm	EUCA	EUPH	FABA	GOOD	GYRO	HALO	HIBB	LEPT	LILI	LOUD	MELP	MELS	MUEH
5	21	2					1	5			3	7	
15	16	1	1					1			2	8	1
35	4	1			5	5		2			1	3	
60	5					2		4			5	4	2
85	4					10		1			6	8	1
100	8				1	9		1			1	1	3
120	12		1	1	2	7			1	1	6	4	2
137	9			2	1	5					5	6	

Depth cm	MYEL	MYMU	MYOP	OPER	PINU	PLAN	POAS	POMA	RANU	RUME	SOLA	SPBR	UNID
5	4	2			2	7	7	2		1			
15	2	1			1	3	12			1			3
35	1			2		4	24	2					3
60	4			4		4	19						1
85	2			3		4	18	1				1	2
100	8					3	20						7
120	11		1	1		1	16	4	1				3
137	192	4	2	5		3	14	10			2	1	5

TAXA NAMES

Code	Taxon	Family (where taxon is genus or species)
ACAC	*Acacia*	Fabaceae
ACAE	*Acaena*	Rosaceae
ADEN	*Adenanthos*	Proteaceae
ADRI	*Adriana*	Euphorbiaceae
AMYE	*Amyema*	Loranthaceae
APIA	Apiaceae	-
ASTL	Asteraceae (Liguliflorae)	-
ASTT	Asteraceae (Tubuliflorae)	-
BANK	*Banksia*	Proteaceae
BEYE	*Beyeria*	Euphorbiaceae
BRAS	Brassicaceae	-
BURS	*Bursaria spinosa*	Pittosporaceae
CALY	*Calythrix*	Myrtaceae
CARY	Caryophyllaceae	-
CASO	*Casuarina* spp. other than *C.stricta*	Casuarinaceae
CASS	*Casuarina stricta*	Casuarinaceae
CHEN	Chenopodiaceae	-
COPR	*Coprosma*	Rubiaceae
CORR	*Correa*	Rutaceae
CRYP	*Cryptandra*	Rhamnaceae
CYPS	Cyperaceae	-
DODO	*Dodonaea*	Sapindaceae
DROS	*Drosera*	Droseraceae
EPAC	Epacridaceae	-
EUCA	*Eucalyptus*	Myrtaceae
EUPH	Euphorbiaceae (other than *Adriana* and *Beyeria*)	-
EXOC	*Exocarpos*	Santalaceae
FABA	Fabaceae (other than *Acacia*)	-
GOOD	Goodeniaceae	-
GREV	*Grevillea*	Proteaceae
GYRO	Gyrostemonaceae	-
HALO	*Haloragis*	Haloragaceae
HIBB	*Hibbertia*	Dilleniaceae
KUNZ	*Kunzea*	Myrtaceae
LEPT	*Leptospermum*	Myrtaceae
	(In Lashmar's Lagoon samples, *Leptospermum* and syncolpate *Melaleuca* are both included in this taxon. In Rocky River and Little Swamp samples, *Leptospermum* and possibly some *Micromyrtus* and syncolpate *Melaleuca* are included).	
LILI	Liliaceae	-
LOUD	*Loudonia*	Haloragaceae
MELA	*Melaleuca*, cf. *M. acuminata*	Myrtaceae
MELH	*Melaleuca*, cf. *M. halmaturorum*	Myrtaceae
	(Lashmar's Lagoon only. May also include some *M. uncinata* and *Eucalyptus* spp.)	
MELP	*Melaleuca* spp.	Myrtaceae
	(Little Swamp only. Pollen grains with polar islands, possibly *M. uncinata*)	
MELS	*Melaleuca* spp.	Myrtaceae
	(Syncolpate *Melaleuca* pollen grains, where distinct from *Leptospermum*)	
MICR	*Micromyrtus*	Myrtaceae
MUEH	*Muehlenbeckia*	Polygonaceae

MYEL	*Myriophyllum elatinoides*	Haloragaceae
MYMU	*Myriophyllum muelleri*	Haloragaceae
MYOP	*Myoporum*	Myoporaceae
MYRT	Myrtaceae (Rocky River only. All Myrtaceae pollen grains too damaged to classify further).	-
OPER	*Opercularia*	Rubiaceae
OTTE	*Ottelia*	Hydrocharitaceae
PETR	*Petrophila*	Proteaceae
PINU	*Pinus*	Pinaceae
PLAN	*Plantago*	Plantaginaceae
POAS	Poaceae	-
PODO	*Podocarpus* (Probably from contamination)	Podocarpaceae
POLY	Polygonaceae (other than *Muehlenbeckia* and *Rumex*)	-
POMA	*Pomaderris*	Rhamnaceae
PORT	Portulacaceae	-
RANU	Ranunculaceae	-
REST	Restionaceae	-
RUME	*Rumex*	Polygonaceae
RUTA	Rutaceae (other than *Correa*)	-
SOLA	Solanaceae	-
SPBR	Bryophyte spores	-
SPFE	Fern spores	-
THRY	*Thryptomene*	Myrtaceae
TRIG	*Triglochin*	Juncaginaceae
UNID	Unknown or too damaged to be identified. Rocky River samples also include some identified but uncommon pollen grains in this classification.	